

THE ROLE OF SURPRISE IN ENHANCING EARLY LEARNING

by
Aimee Elyse Stahl

A dissertation submitted to Johns Hopkins University in conformity with the
requirements for the degree of Doctor of Philosophy

Baltimore, Maryland
April, 2015

© 2015 Aimee Stahl
All Rights Reserved

Abstract

Given the overwhelming quantity of information available from the environment, how do young learners know what to attend to and learn about versus what to ignore? In my dissertation I propose that one mechanism for narrowing the learning space is for infants and children to use violations of prior expectations as special opportunities for learning.

In Experiment Series 1, I showed 11-month-old infants events that violated core expectations about object behavior, or events that were nearly identical but did not violate expectations. I then taught infants new information about the object that participated in the event, and found that infants learned more effectively following surprising events than expected ones. Control experiments confirmed that this learning was not due to longer perceptual exposure to surprising events or to a general preference for objects that violated expectations, and that the learning enhancement only benefitted those objects that participated in the surprising event.

In Experiment 2, I asked whether infants would preferentially seek information from and explanations for objects that behaved surprisingly. I again showed 11-month-old infants perceptually matched surprising and expected events, and gave them the opportunity to explore the object from the event and a new object. Infants who witnessed the surprising event selectively explored the very object that violated their expectations, and more impressively, engaged in hypothesis testing behaviors that reflected the particular kind of violation seen.

Finally, in Experiment Series 3 I asked whether this learning enhancement following surprising events is a more general feature of human learning. I examined

whether preschool-aged children in a museum setting would learn novel words more effectively following surprising than expected events. I found that, like infants, children showed enhanced learning following events that violated their expectations, and their learning was beneficially constrained to the entity that behaved surprisingly.

Together, my experiments show that when infants and children witness an object defy their expectations, they learn about it better, explore it more, and seek explanations for that object's behavior. Thus, early in life, expectancy violations offer a wedge into the problem of what to learn.

Advisor: Dr. Lisa Feigenson

Readers: Dr. Lisa Feigenson

Dr. Justin Halberda

Dr. Marina Bedny

Dr. Barbara Landau

Dr. Roberta Michnick Golinkoff

Acknowledgments

Writing this dissertation has been a relatively rapid process, but everything that made this document possible has spanned the last five years. I must thank a number of people in both my personal and professional life who have encouraged me along the way.

I must first and foremost thank my parents, who have been unconditionally supportive my entire life. They have always let me find my own way, while offering their love and guidance at every step. Thanks to my mom for our twice-daily (sometimes more!) phone calls as I walk to and from Ames Hall, and for being my best friend. Thanks to my dad for always checking in and asking questions about graduate school, publishing, and research, and for always seeming to know the answers to my “adult life” questions. They are the greatest parents anyone could ask for, and I don’t say that enough. Thanks to Drew, who has always been an inspiration as a strong, smart, and motivated older brother. And thank you to my grandmothers, Shirley and Judy, who have been stellar role models my entire life and my number one cheerleaders.

Thank you to my almost-husband, Zach. In our eleven years together we have been through high school, college, jobs, moves, and graduate school, and it has all paid off. We have always followed our professional dreams independently, but supported each other (from afar) at each moment. We can finally merge our lives in a few short months, and I cannot wait for what lies ahead. Some say it was our preschool trip to the bagel factory in 1989 that sealed our fate together; I say it is because he has been a constant source of support, laughter, comfort, and fun over the last decade. He has embraced me as a partner, a woman, a scientist, a friend, a southern barbeque enthusiast, and a travel

buddy. I never could have made this journey without him. Thanks to his family – Robin, Arthur, and Jesse – who have welcomed me in as one of their own.

Thank you to my friends and peers in the department, especially Tony Sali, Judith Asem, and Heena Lakhani, who have been there from the beginning. We've shared our struggles and successes every step of the way, and our office therapy sessions have kept us going for all these years. We have truly grown together. Thanks to my other colleagues in the department and to my current and former labmates for teaching me all sorts of things, from baby tricks to statistical analyses: Jenny Wang, Darko Odic, Hrag Pailian, Melissa Libertus, Mariko Moher, Reba Rosenberg, and Jenn Zosh. A very special thanks to Melissa Kibbe, who has been an invaluable resource as a scientist, friend, and colleague. Our daily g-chats keep me sane, stimulated, and full of laughter each and every day. Thank you to all of my dear non-academic friends who have been there for me for years or even decades: Ali Groden, Talia Halperin, Dana Wander, and Amy Blauner.

Thanks to all of my research assistants, especially Jessica Taggart, Julissa Veras, Susan Folsom, Marisa Santoru, Bridget McGowan, and Carli Heiman, for tirelessly running and coding hundreds of babies and kids, always with a smile. Working with these talented students has been a highlight of my graduate career, and I am a better mentor and teacher because of them. None of my research would be possible without the parents and children who participated in these experiments. I feel extremely lucky to be able to combine two of my favorite things: science and babies. Going to work each day has been a joy, and I am indebted to them for their time and generosity.

Thank you to the professors along the way who helped me reach this point in my career, especially Dr. Beth Morling, who plucked me from her Research Methods class

and started me on my journey as an undergraduate research assistant; and Dr. Paul C. Quinn, who showed me my first joys and challenges of working with infants and inspired me to take the leap into academia. A special thanks to Dr. Roberta Golinkoff for taking me on as her lab manager and treating me like a graduate student from the beginning. I am grateful that we continue to work together to this day. Of course, thank you to the other members of my committee, Dr. Marina Bedny and Dr. Barbara Landau, for joining me on the last step of this journey.

I owe a huge thanks to Justin Halberda, who thinks like no one else I have ever met. He has challenged and inspired me to always think outside of the box. He has taught me that taking risks pays off, and that being compassionate goes a long way. His jokes are uniquely hilarious, and his generosity is unmatched.

And most of all, thank you to my advisor, Lisa Feigenson. Aside from being brilliant and the voice of reason (and always right!), you are immensely kind, eternally supportive, and incredibly humble. You have thought of me as a person first, and a student second, which has been refreshing and motivating. You have been, without question, the best advisor I could have possibly imagined. I always feel better after leaving your office – about data, about manuscripts, and about life. You have encouraged and challenged me in the most meaningful ways, and I am forever grateful to have had you as my biggest supporter these last five years. I am a better writer, speaker, scientist, teacher, and mentor because of you. I hope my role in another student's life is even half as meaningful as yours has been in mine. Lisa and Justin, you have both fundamentally changed me as a thinker and as a person. I cannot adequately express my gratitude in words. Thank you.

Table of Contents

Abstract	ii
Acknowledgements	iv
List of Figures	ix
1. Introduction	1
1.1 The importance of learning and its challenges	2
1.2 The importance of core knowledge and its challenges	5
1.3 Uncovering infants' knowledge	13
1.4 The role of prediction error in animal and adult learning	17
1.5 Children's use of prior knowledge for learning	21
2. Question 1: Does detecting an unexpected event enhance infants' learning?	27
2.1 Experiment 1.1 Infants' learning following expected and unexpected events ...	28
2.2 Experiment 1.2 Ruling out perceptual preference for surprising objects	38
2.3 Experiment 1.3 Infants' learning about new objects following unexpected events	41
2.4 General discussion of Experiments 1.1-1.3	43
3. Question 2: Do infants selectively explore and seek explanations about objects that behaved surprisingly?	44
3.1 Experiment 2 Infants' exploration following expected and unexpected events..	45
3.2 General discussion of Experiment 2	58
4. Question 3: Do children learn more effectively following violation events?	60
4.1 Experiment 3.1 Children's learning of novel verbs following expected and unexpected events	62
4.2 Experiment 3.2 Children's learning of novel nouns following expected and unexpected events	74
4.3 Experiment 3.3 Ruling out perceptual preference for surprising objects	77
4.4 Experiment 3.4 Children's learning about new objects following unexpected events	79

4.5 General Discussion of Experiments 3.1-3.4	83
5. General Discussion	84
6. References.....	94
7. Curriculum Vitae	113

List of Figures

Figure 1. Event sequence of Solidity Condition in Experiment 1.1.	32
Figure 2. Event sequence of Continuity Condition in Experiment 1.1.	35
Figure 3. Looking times to event outcomes in Experiment 1.1.	36
Figure 4. Learning results of Experiments 1.1-1.3.	38
Figure 5. Event sequence of Solidity Condition in Experiment 2.	49
Figure 6. Event sequence of Support Condition in Experiment 2.	52
Figure 7. Looking times to event outcomes in Experiment 2.	54
Figure 8. Exploration results of Experiment 2.	55
Figure 9. Hypothesis-testing results of Experiment 2.	57
Figure 10. Event sequence of Spatiotemporal Continuity event in Experiment 3.1.	68
Figure 11. Event sequence of Featural Continuity event in Experiment 3.1.	72
Figure 12. Results for Experiment 3.1.	74
Figure 13. Results for Experiment 3.2.	76
Figure 14. Results for Experiment 3.3.	79
Figure 15. Novel stimuli in Experiment 3.4.	81
Figure 16. Results for Experiment 3.4.	83

1. Introduction

Human knowledge is remarkably sophisticated – from our technical knowledge of scientific instruments to our understanding of the social world. How does this rich body of knowledge emerge? Theorists have highlighted the importance of different aspects of the origins of knowledge in their views of development. On the one hand, some have proposed a rich starting state (e.g., Carey, 2009; Spelke & Kinzler, 2007; Spelke & Newport, 1998; Plato, 380 B.C.E/1892), which is often thought of as the product of evolutionary pressures that have come, over millions of years, to provide minds with an initial model of the world. The strength of such an initial model is that it can support strong predictions and guide behavior in the absence of specific experiences; yet it must manage to do so while still being flexible enough to acquire new knowledge. On the other hand, some thinkers have proposed a far sparser initial state accompanied by robust learning mechanisms (e.g., Skinner, 1977; Piaget, 1954; Helmholtz, 1867/1962). On this view, there is no initial model of the world (or only a simple perceptual one); instead our model of the world is built from experience, and learning requires forming associations between experiences. However, given that there is so much one could conceivably learn about the world, such learning must be constrained if it is to support rapid and accurate changes in knowledge and behavior.

Historically, thinkers have stressed either the role of the initial state (see Fodor, 1981 for an argument claiming that concepts must be innate and cannot be learned) or the role of learning (see Skinner, 1977 for an argument claiming that all experiences are associations between the body and the environment). Broadly, the goal of this dissertation is to explore the synergy between a rich initial state and learning. Throughout, the

research presented here aims to embrace both innate knowledge and learning to investigate the idea that infants and children might be empowered to scaffold novel learning from a rich starting state. In this way, innate knowledge might constrain the learning challenge faced by the developing mind.

1.1. The importance of learning and its challenges

Early associationist views posited that humans are equipped to form associations between stimuli, and that knowledge is the product of learning these associations. For example, Berkeley proposed that humans visually perceive depth not by automatic, unlearned mental computations over geometrical relations in the distal environment (as Descartes proposed, 1637/1971), but by associating the physical feeling of changes in the eyes with the haptically perceived distances of objects. Through these associations, he claimed that humans could eventually *learn* to perceive depth (1732/1910; see also Helmholtz, 1867/1962). Likewise, B.F. Skinner (1977) posited that human experience is shaped by contingencies between the body and environment, and denied the role of the mind and cognitive states. Theorists along these empiricist lines have proposed that humans are born with a cognitive architecture that is content-free and domain-general (Simpson, Carruthers, Laurence, & Stich, 2005 for review). On this model-free view of learning, infants and children start with no expectations and thus have to construct a model of the world from thousands of sensory experiences (e.g., Piaget, 1954; Quine, 1960; see also Locke, 1690/1975; James, 1890/1981).

Indeed, young infants are adept learners. Fetuses and newborn infants recognize their mother's voice and native language (e.g., DeCasper & Fifer, 1980; Kisilevsky et al.,

2003; Moon, Cooper, & Fifer, 1993) and can learn to discriminate speech sounds while still in utero (e.g., Partanen et al., 2013; Moon, Lagercrantz, & Kuhl, 2013). Additionally, newborns and older infants can parse visual and auditory streams by learning associations between elements (e.g., Teinonen, Fellman, Näätänen, Alku, & Huotilainen, 2009; Bulf, Johnson, & Valenza, 2011; Saffran, Aslin, & Newport, 1996; Kirkham, Slemmer, & Johnson, 2002). Thus, accumulating experience is a powerful learning tool for even the youngest minds.

However, the world is a complex and dynamic place; at any given moment, noisy, ambiguous information bombards the observer – indeed, too much information to encode and learn from at once. Consider even a simple case, one that seemingly skirts the problem by simplifying the input: an infant attempting to learn about a single object, like a cup. Despite the simplicity of this scene, there is a problem – the infant could perceive a finite array of perceptual data, but have an infinite variety of understandings of that data: she could learn about the cup’s shape, size, color, reflectivity, texture, sub-parts (and their corresponding shapes, sizes, colors, reflectivity, and textures), distance from the infant (or distance from any other entity), its velocity as it moves, and so on. Given this surfeit of potential cognitive descriptions, how does a thinker possibly know what to attend to, remember, and learn about? This problem may be particularly challenging for the youngest minds, those of infants and children, who arguably have the most learn, yet limited cognitive resources (e.g., Ruff & Capozzoli, 2003; Colombo, 2001; Rovee-Collier, 1999; Ross-Sheahy, Oakes, & Luck, 2003).

This problem – that learning is often highly underdetermined – has been noted by many previous theorists (e.g., Tenenbaum, Kemp, Griffiths, & Goodman, 2011; Perfors,

Tenenbaum, Griffiths, & Xu, 2011; Chomsky, 1980a; Chomsky, 1980b; Plato, 380 B.C.E./1892; Pinker, 1994). Without a filter for determining what to learn, or a teacher to provide guidance (Csibra & Gergely, 2009), information overload can, in practice, make learning impossible. One might suggest that a strong empiricist and model-free view of learning (e.g., Piaget, 1954; Berkeley, 1732/1910; Skinner, 1977; Elman, Bates, & Johnson, 1996) puts learners in a nearly impossible predicament: they would not only need to accumulate thousands of hours of experience, but also determine which associations among those experiences are meaningful and which should be ignored.

In addition to filtering out irrelevant information, learners often must make inferences over sparse data. For example, learning a grammar, acquiring new words, or constructing/enriching a concept requires that children go well beyond the immediate input, abstracting in powerful ways (Chomsky, 1980a; Chomsky, 1980b; Pinker, 1994; Tenenbaum et al., 2011; Xu & Tenenbaum, 2007; Spelke & Newport, 1998; Senghas, Kita, & Özyürek, 2004). The infant trying to learn about the cup in the example above might be successful in making an association between the word “cup” and the sight of the cup, but she must employ far more abstract knowledge to form a *concept* of cups such that she may appropriately extend the newly learned word to novel exemplars, and eventually use the word in an entirely new grammatical sentence.

What is more, the empiricist perspective implies that there must be radical conceptual change across development from infancy to adulthood to achieve the mature knowledge state. Piaget (1954) famously suggested that infants and young children see the world in a radically different way than do adults. Yet, as Spelke and Newport (1998) point out, it might be more parsimonious to attribute infants with knowledge that is

shared with adults, such that less radical change is implicated. In fact, it might be this shared body of knowledge, present throughout the lifespan and developing in the absence of specific experience, that could offer a wedge into the hard problem of narrowing the learning space.

1.2. The importance of core knowledge and its challenges

One solution to the learning challenge might be for young minds to use prior knowledge (perhaps innate knowledge) to guide learning. This kind of model-based learning offers a filter for determining what to learn and what to ignore; if the young mind is already equipped with structured expectations, then learning could, in principle, be preferentially directed to cases when these expectations are not met – that is, to situations in which there is something new to learn.

Before evaluating the plausibility of this idea, we might first ask whether there is in fact evidence for early structured knowledge such that it may be available to shape learning. A major challenge to answering this question has been methodological – how might it be possible to characterize the early knowledge state of the human mind?

Although infants undoubtedly learn much about the world over the first year of life, some aspects of the world appear to be represented even prior to learning. These cognitive primitives, sometimes collectively called “core knowledge,” are thought to be the product of evolutionary pressures for organisms to solve domain-specific problems, particularly in the domains of objects, space, number, actions, and perhaps other minds (Spelke & Kinzler, 2007 for review). The solutions to these problems appear to be conserved over ontogeny and phylogeny. For example, evidence of core knowledge is observed in human

infants and adults (e.g., Huntley-Fenner, Carey, & Solimando, 2002; van Marle & Scholl, 2003), and even newborn creatures show evidence of core knowledge (Izard, Sann, Spelke, & Sterri, 2009; Regolin & Vallortigara, 1995). Additionally, core knowledge has been observed in a variety of species, including non-human primates, rats, fish, and chicks (e.g., Hauser & Carey, 2003; Santos 2004; Santos & Hood, 2009; Spelke & Lee, 2012; Regolin & Vallortigara, 1995). Core knowledge appears largely independent of specific experience, as it emerges under controlled rearing conditions (e.g., Chiandetti & Vallortigara, 2010) and across diverse cultures (Everett 2005; Gordon, 2004; Dehaene, Izard, Pica, & Spelke, 2006).

The earliest and perhaps best-documented case of core knowledge is that of the “object concept.” Animals from a variety of species encounter and must reason about mid-sized, three-dimensional objects in their immediate environment. Expectations about the typical behavior of objects (i.e., recognition of the actions that objects can and cannot undergo) are likely to be beneficial throughout the lifespan. Indeed, early in the first year of life, human infants demonstrate sensitivity to principles of object behavior.

Spelke (1990; 1994) has proposed that core knowledge of objects includes expectations about three central properties, each of which has been supported through empirical research with infants (and with some primates, for review see Santos & Hood, 2009). One such principle is that objects cannot move without contact from other entities (e.g., Woodward, Phillips, & Spelke, 1993; Leslie & Keeble, 1987). For example, infants look longer when an individual object moves on its own accord, compared to when one moving object comes into contact with and launches another (e.g., Woodward et al., 1993).

A second principle is that objects are cohesive entities that maintain their connectedness and boundaries (e.g., Kellman & Spelke, 1983; Spelke, Phillips, & Woodward, 1995; Spelke & Van de Walle, 1993). For instance, infants look longer when a hand grasps an object but only the top portion of the object lifts into the air, compared to when the entire object is lifted (Spelke, Breinlinger, Jacobson, & Phillips, 1993). Additionally, infants expect that a rod that moves behind an occluder is one cohesive object rather than two parts with a gap in between (Kellman & Spelke, 1983).

A third well-studied principle of early object knowledge is continuity: objects move on continuous paths and continue to exist when out of sight (e.g., Spelke, Kestenbaum, Simons, & Wein, 1995; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Baillargeon, 1987b; Baillargeon, Spelke, & Wasserman, 1985; Baillargeon & Graber, 1987; Wilcox, Nadel, & Rosser, 1996). In one study, 2.5-month-old infants saw a toy hidden behind one of two spatially separated opaque screens. When the screens were lifted, infants looked longer when the toy was revealed behind the other screen, compared to when it was revealed in its original hiding location (Wilcox et al., 1996). In another study, 5-month-old infants were shown a screen that rotated 180 degrees. A box was then placed out of view behind the screen, and the screen either rotated 180 degrees as before, or it only rotated 120 degrees as if it had been stopped by the box. Infants looked longer when the screen rotated the full 180 degrees, suggesting that they represented the box's existence even though they had no perceptual contact with it (Baillargeon et al., 1985).

In fact, infants maintain robust representations of hidden objects in the absence of perceptual input over a delay of several minutes (Luo, Baillargeon, Breukner, & Munakata, 2003), and infants can even represent the featural properties of hidden objects

(Baillargeon, 1987b; Baillargeon & DeVos, 1991). For instance, Baillargeon (1987b) showed infants either a tall or a short object hidden behind a screen. The screen rotated backwards the same amount in both cases, but the rotation was only possible when the short object was behind the screen. Even though these two test events were perceptually identical, infants looked longer when the tall object had been placed behind the screen than when the short object had been placed behind the screen. This finding suggests that infants must have represented both the existence of the object and the property of its height.

Recent evidence suggests that not only can domestic chicks represent objects through occlusion, but they, like infants, can represent featural information about hidden objects (Chiandetti & Vallortigara, 2010). Chicks were reared in an entirely controlled setting: each was alone in a cage with a singular object, a red cylinder, hanging in the center. Chicks imprinted on this object, as it was the only available mid-sized object in their environment. At test, chicks watched as the red cylinder moved toward two screens, at which point their view was covered by an occluder. The occluder was lifted to reveal, for example, one screen that was tilted backward 45 degrees, and one that was tilted backward 10 degrees (which would have been too flat to cover the cylinder). Chicks preferentially chose the screen that was tilted 45 degrees, indicating that they represented not only the existence of the cylinder, but its height as well. Chicks also successfully used height and width of the screens to reason about the location of the hidden cylinder, despite never having had experience with object occlusion (Chiandetti & Vallortigara, 2010).

This last principle, that of object continuity, has some interesting corollaries. One corollary is that no two objects can occupy the same space at the same time – in other words, infants appear to expect that one solid object cannot pass through another (e.g., Baillargeon, et al., 1985; Spelke et al., 1992; Baillargeon, 1986). Infants' core knowledge of solidity has been demonstrated in numerous studies at various ages. For example, 2.5-month-old infants show increased looking when a moving ball appears to pass through a wall, and 4-month-olds show increased looking when a falling ball appears to pass through a shelf (Spelke et al., 1992). Likewise, infants at 3.5, 4.5, 5 and 7 months look longer when a rotating screen appears to pass through an object placed behind the screen than when the screen is stopped in its path by the object (e.g., Baillargeon, 1987a; Baillargeon et al., 1985; Baillargeon, 1987b; Baillargeon, 1991). Six- and 8-month-olds look longer when a traveling toy car emerges from behind an occluder when a block had been placed in its path, compared to when the block was placed just behind but not impeding the path (Baillargeon, 1986). These results are consistent with the interpretation that infants maintained representations of both the barrier and the moving object during the occlusion, represented the moving object's trajectory and anticipated that it would continue to travel on its path, and recognized that the object could not pass through the space occupied by a barrier. Notably, similar demonstrations of solidity knowledge have been observed in toddlers (Mash, Clifton, & Berthier, 2002) rhesus monkeys (Santos & Hauser, 2002), and domesticated dogs (Kundey, De Los Reyes, Taglang, Baruch, & German, 2010).

Together, these studies show that infants have sophisticated expectations about object behavior starting from early in infancy. One reason to think that this object

knowledge is not built from simple perceptual features is that it is specific to certain entities: namely, infants have expectations about mid-sized objects, but not non-cohesive substances. For instance, in one set of studies 8-month-old infants saw a rigid object, which was shaped like a pile and coated with sand, placed on a stage. Importantly, even though the object had a sand-like texture and color, it moved as a cohesive whole with stable boundaries. After this sand-object was placed on the stage, it was covered by a screen, and a second identical sand-object was added behind the screen. Infants looked longer when the screen was lifted and only a single sand-object was revealed than when two sand-objects were revealed, showing that infants successfully updated their representation of the hidden objects. However, when infants viewed an identical sequence of events but with actual sand poured onto the stage into piles, they failed to represent this non-cohesive substance and could not track it through occlusion: they showed no expectations about how many piles of sand should be behind the occluder (Huntley-Fenner et al., 2002). Other studies have demonstrated similar success with solid objects (e.g., Wynn, 1992) but failure with non-cohesive collections of objects (Chiang & Wynn, 2000).

Additionally, the principles that govern the object concept are domain-specific – they apply to mid-sized objects but not to all physical entities. For example, infants expect that objects cannot move without contact from other entities, but the same expectations do not hold for animate agents. Unlike inanimate objects, infants appear to understand that humans can indeed move on their own accord and do not require contact with another agent or entity to travel on a path (Woodward et al., 1993). Moreover, infants expect that social agents (e.g., humans with hands) can have goals and intentions,

but inanimate objects (e.g., rods, claws, and machine-like pincers) cannot (e.g., Woodward, 1998; Meltzoff, 1995). And 5-month-old infants expect that objects trace spatiotemporally continuous paths (Spelke et al., 1995), but do not appear to hold this expectation for people (Kuhlmeier, Bloom, & Wynn, 2004).

The above evidence suggests that infants have domain-specific expectations about the behavior of objects that is available from the first few months of life, and that is shared with several non-human species – in other words, infants have core knowledge of objects. Like objects, other domains of core knowledge are also shared across development and across species. For example, infants, adults, and non-human animals share the core system of approximate number. Non-verbal number representations are noisy and abstract (i.e., not dependent on any one sensory modality), and support comparison and combination over represented quantities (Feigenson, Dehaene, & Spelke, 2004 for review). Core knowledge of social agents allows humans and non-human animals to represent the goals, intentions, and mental states of animate agents (e.g., Woodward, 1998; Meltzoff, 1995; Gergely & Csibra, 2003; Onishi & Baillargeon, 2005; Flombaum & Santos, 2005). Finally, research on the core domain of space demonstrates that, among other types of spatial representations, young humans, adults, and non-human animals reorient in space using the geometry of extended surfaces in the environment (e.g., Hermer & Spelke, 1996; Spelke & Lee, 2012; Dehaene et al., 2006), although this ability can be specifically impaired in some populations (Lakusta, Dessalegn & Landau, 2010).

Critically, positing core knowledge across these various domains does not deny the roles of change, development, or learning (Spelke & Newport, 1998; Spelke, 1998;

Baillargeon, 1999). The initial state of the mind cannot be static; rather, it must be responsive to experience and learning. Specifically, learning might be guided by domain-specific constraints that are evolutionarily ancient (Gallistel, 1989). Thus, one might understand core knowledge as a learning theory – a starting model of the world that scaffolds future learning. For example, 3-month-old infants expect that an object should be stable when it is in full contact with a platform underneath it, and they expect the object to fall when it is pushed beyond the surface of the platform and has no contact with it (Needham & Baillargeon, 1993). However, it is not until 6.5 months that infants reason about how much contact the object must have with the platform to be supported (Baillargeon, Needhman, & DeVos, 1992). This suggests that while infants start with knowledge that an object must have *some* contact with a platform object to be supported, their reasoning about object support is refined over time. That is, infants' initial state posits that contact is the relevant variable when reasoning about an object's support (and not its color, for example), and they refine their theory by gathering evidence from relevant experiences with the world.

Far from obviating the need for learning, core knowledge may be a foundational understanding from which learning begins. One way this could be so is if core knowledge offers a wedge into the hard problem of knowing what to learn. If a learner has a basic repertoire of core expectations about the world, then detecting a violation to these expectations – where what was predicted conflicts with what is observed – might signal a special opportunity for learning.

1.3. Uncovering infants' knowledge

A chief innovation in the effort to characterize preverbal knowledge, and in demonstrating the existence of the core knowledge domains reviewed above, was the discovery that a simple behavioral measure could be used to make inferences about infants' mental lives. Because preverbal infants cannot use language to express their thoughts, researchers turned to a behavior that typically developing infants spontaneously produce nearly every waking moment: looking. Looking is a functional behavior – it helps to allocate attention and extract information from the world starting from birth (Fantz, 1964). Most of the earliest studies using looking time as a dependent measure sought to characterize infants' perceptual abilities. Fantz (1964) examined visual exploration in newborns, and found that they can direct their gaze, discriminate between stimuli, and importantly, remember what they had seen. The habituation method has been one means by which developmental psychologists have determined infants' perceptual abilities. Over the course of repeated exposure to a stimulus (e.g., a high contrast visual pattern), Fantz found that infants gradually decreased their looking time, indicating that they remembered some aspect of that stimulus. Following this period of habituation, when a novel stimulus (e.g., a new pattern) was shown, infants regained visual interest, demonstrating that they discriminated between this new stimulus and the one from habituation (Fantz, 1964). Other studies compared infants' visual preference for one visual stimulus over another as a means to measure perceptual discrimination abilities (e.g., Fantz, 1963; Teller, 1979).

More recent work using looking time has sought to make inferences about infants' *conceptual* knowledge. The violation-of-expectation (VOE) method has been especially

fruitful in the search to uncover infants' knowledge, and has been invaluable in the efforts to characterize core knowledge in particular. In this paradigm, infants often are habituated to a possible event, like a screen rotating forward and back 180 degrees on an empty stage, as described earlier (but for a design using VOE without familiarization, see Wang, Baillargeon, & Brueckner, 2004). Infants then see two new types of test events: one that adults would judge to be expected (e.g., the screen rotating only 120 degrees when a box is placed out of view behind the screen), and one that adults would judge to be surprising (the screen still rotating 180 degrees when a box is placed out of view behind it). In this example, infants systematically look longer at the outcome that adults judge as surprising, in which the screen appears to pass through a solid object. This pattern of longer looking to surprising events is quite general: across hundreds of published studies, infants look longer when basic expectations are violated, including expectations generated by core knowledge (Spelke & Kinzler, 2007). For example, infants detect violations and look longer when a hidden object vanishes (Baillargeon et al., 1985), when five objects added to five objects only yields five objects (McCrink & Wynn, 2004), and when a social agent approaches someone who was previously mean rather than someone who was previously nice (Kuhlmeier, Wynn, & Bloom, 2003).

Although the VOE method helped usher in a new way of thinking about early knowledge, some developmental psychologists voiced objections to using looking time to make claims about conceptual knowledge. One concern of looking time critics is that infants might learn about the stimuli over the course of habituation or familiarization. If infants repeatedly see a possible event during habituation, followed by two test events, one of which is possible (and is conceptually familiar but perceptually novel) and the

other impossible (and is perceptually familiar but conceptually novel), then perhaps infants learned over the course of the experimental session what is possible. On this account, infants' elevated looking reveals sensitivity to the statistics of the experimental sequence, not abstract knowledge about object behavior. However, some studies did not involve habituation or familiarization phases in their design (e.g., Wynn, 1992; Wang et al., 2004), yet found that infants still looked longer at the impossible event. Another study demonstrated that infants familiarized to a possible event (object hidden in location A is retrieved from location A) looked longer at an impossible event (object hidden in location A is retrieved from location B), but not vice versa, indicating that infants could not be taught that an anomalous event was possible, at least over the course of a typical laboratory session (Newcombe, Sluzenski, & Huttenlocher, 2005).

Another objection that has been raised focuses on the kinds of inferences that can be made from infants' patterns of looking (e.g., Sirois & Marsechal, 2002; Jackson & Sirois, 2009; Haith, 1998). Aslin (2007) discusses the ambiguities of the looking-time measure, noting that longer looking at a stimulus could reflect various processes, including attention, surprise, orienting, novelty, and recognition. Haith (1998) and others have argued that the most parsimonious explanation of looking time data is that infants' looking is guided by perceptual preferences rather than by conceptual knowledge.

The well-studied case of object knowledge can help illustrate these issues. Infants' longer looking at impossible outcomes, like one object appearing to pass through another, has been taken as evidence that infants *represented* the object once it was hidden, *predicted* that it would continue to exist and not pass through another object, and were *surprised* when these *expectations* were violated (e.g., Baillargeon et al., 1985). Haith

(1998) claims that the language used, including the terms *represent*, *surprise*, *reason*, *infer*, etc., are too strong and overestimate infants' capabilities. These "psychological felonies" (Haith, 1998, pg. 168) cast doubt on the conceptual knowledge attributed to infants, and on the measure of looking time as a whole. Instead of interpreting infants' longer looking to mean that infants were surprised by the conceptually novel outcome, these researchers claim that infants are looking at what became perceptually familiar over the course of habituation (Jackson & Sirois, 2009; Cohen & Marks, 2002).

For example, Wynn (1992) and Huntley-Fenner et al. (2002) offered data to suggest that 5- to 8-month-old infants can maintain and mentally update representations of hidden objects. When infants see one solid object covered by a screen, and another added behind the screen, they look longer when one object is revealed compared to two objects. Cohen and Marks (2002) proposed that infants look longer to the "unexpected" outcome not because infants mentally represented both hidden objects, but rather because the "unexpected" outcome was more perceptually familiar – that is, the outcome that infants preferred was perceptually identical to the starting state of the display (containing just a single object) before occlusion and the second object was hidden. This account assumes no representational capacities on the part of the infant. However, the finding that infants fail to look longer at the unexpected (and perceptually familiar) outcome when non-cohesive entities (e.g., sand) are used suggests that mere perceptual familiarity cannot be driving infants' performance (Huntley-Fenner et al., 2002; Chiang & Wynn, 2000). Instead, the conceptual interpretation proposes that solid objects are privileged, such that infants can track them, represent them once hidden, update these representations, and ultimately look longer when their expectations are violated.

What is more, other methods and measures have converged on similar findings: for instance, infants have been shown to represent hidden objects in studies that measure looking (e.g., Wynn, 1992; Baillargeon, 1987b), reaching (Feigenson & Carey, 2003), and forced choice (Feigenson, Carey, & Hauser, 2002). In addition to these behaviors, surprising events can induce changes in social referencing behavior (Walden, Kim, McCoy, & Karass, 2007), facial expression (Camras et al., 2002), pupil dilation (Jackson & Sirois, 2009; Gredebäck & Melinder, 2010), and brain activity (Wilcox, Bortfeld, Woods, Wruck, & Boas, 2005; Berger, Tzur, & Posner, 2006). From the behavioral to the physiological, these responses have been taken to indicate the detection of a discrepancy between what was expected and what was observed, and have been documented across domains of core knowledge.

1.4 The role of prediction error in animal and adult learning

Given the abundance of evidence that infants exhibit systematic behaviors correlated with surprising events (including longer looking), it is noteworthy that the purpose of these surprise responses remains entirely unknown. In particular, it is unknown what the cognitive consequences of experiencing an expectancy violation might be. One possibility is that surprise signals a special opportunity for learning: infants who see an event that violates their expectations might experience enhanced learning about the objects that behaved surprisingly.

Although this hypothesis is untested in human infants, research with non-human animals suggests that violations of expectation can influence learning. In most of these studies, violation of expectation, or surprise, is operationalized as prediction error – a

quantifiable difference between what the animal expected to happen and what the animal actually observed. When prediction errors are large, the animal might modify its behavior to more successfully predict events in the future (i.e., to learn); when prediction errors are small or zero, little modification is necessary since events unfolded as predicted (Schultz & Dickinson, 2000; Courville, Daw, & Touretzky, 2006). The highly influential Pearce Hall model of learning (Pearce & Hall, 1980) offers an account of this effect: it posits that an unexpected unconditioned stimulus increases an animal's attention to, and thereby the associability of, a conditioned stimulus that accompanied that surprising event. Therefore, large prediction errors lead to faster learning.

As an illustration, consider two groups of rats trained that the appearance of a light reliably predicts the receipt of a shock. At first, this pairing is unexpected and the rats' prediction error is large, but after many trials, the rats experience almost no prediction error. Next, the light is paired with a new stimulus, an auditory tone. For one group of rats, the unconditioned stimulus of the shock remains exactly the same. For these rats, the tone acquires no associative strength because the light already perfectly predicts the shock (this phenomenon is known as "blocking"). A separate group of rats experience the compound stimulus of the light plus the tone, but now followed by a stronger shock or an additional shock, which is considered to be a "surprising" event. In this case, the unexpected unconditioned stimulus (the extra shock) elicits a large prediction error. Blocking to the tone does not occur; the tone signaled a change in the unconditioned stimulus (the surprising extra shock), and thus the rats learn about the conditioned stimulus that predicted that surprising event (e.g., Kamin, 1969; Pearce & Hall, 1980; Rescorla & Wagner, 1972). Surprise can also be operationalized in other

ways; rather than receiving extra shock, rats can experience enhanced learning about the conditioned stimulus if the unconditioned stimulus is temporally delayed or altogether omitted (Dickinson, Hall, & Mackintosh, 1976), or if the conditioned stimulus surprisingly predicts a neutral stimulus (Wilson, Boumphrey, & Pearce, 1992).

In addition to influencing rates of learning in rodents, prediction error has been shown to play a role in learning in non-human primates. Monkeys in a blocking experiment learned more effectively about a conditioned stimulus that surprisingly predicted a reward (Waeleti, Dickinson, & Schultz, 2001). Many studies suggest that dopamine neurons code prediction errors, such that they show increased responses for unpredictable than predictable rewards, with these responses then decreasing with continued learning (e.g., Waeleti et al., 2001; Hollerman & Schultz, 1998; Schultz, Dayan, & Montague, 1997; Roesch, Esber, Li, Daw, & Schoenbaum, 2012 for review; Schultz & Dickson, 2000 for review).

Additionally, monkeys are more likely to adjust their behavior following surprising than predictable events (Hayden, Heilbronner, Pearson, & Platt, 2011). When they receive an expected large reward, they are likely to maintain the same strategy to receive reward on the next trial. However, if monkeys receive a large reward that was surprising, they are more likely to switch their strategy, indicating that they may have interpreted the surprising event as indicating a change in the contingency between the reward and the conditioned stimulus. Thus, monkeys are more likely to explore new strategies rather than exploit a current one following surprising events. Furthermore, the neural basis for this effect has begun to be revealed – neurons in the anterior cingulate cortex (ACC) increase in firing rate for these improbable rewards (Hayden et al., 2011).

Similar to the studies with non-human species, most research on the effects of surprise on learning in human adults have relied on teaching observers a probabilistic structure, violations of which can be detected as the observer learns the contingencies. The dorsolateral prefrontal cortex (DLPFC) (Fletcher et al., 2003; den Ouden, Friston, Daw, McIntosh, & Stephan, 2009), ACC (e.g., Carter et al., 1998; Brown & Braver, 2005), and striatum (e.g., McClure, Berns, & Montague, 2003; den Ouden et al., 2009; O'Doherty et al., 2004; Hare, O'Doherty, Camerer, Schultz, & Rangel, 2008) have been implicated in detecting conflict between what was expected and what was observed. Surprising events induce changes in activity in these areas in conditioning tasks in which a stimulus predicted reward (e.g., juice; McClure et al., 2003; O'Doherty et al., 2004), as well as incidental learning tasks in which stimuli had no intrinsic hedonic value (e.g., den Ouden et al., 2009; Wacongne et al., 2011).

One experiment with human adults (den Ouden et al., 2009) presented observers with an incidental learning task in which they were to detect the presence of an auditory-visual target among other auditory and visual stimuli. The auditory distractors predicted whether or not a visual distractor would appear. Observers exhibited increased activity in the DLPFC when the presence or absence of a visual target was expected compared to when it was surprising. Additionally, observers exhibited increased activity in primary visual cortex (V1) and striatum when an expected visual target was omitted or an unexpected target was present. These responses increased over time as learning improved, whereas responses to predicted stimuli decreased. Critically, a model showed that there was an increase in connectivity between primary auditory cortex (A1) and V1 for trials in which the presence or absence of a visual target was surprising (i.e., the auditory cue did

not accurately predict the visual target), which is taken as an index of learning. That is, increasing the connection between these two areas can help reduce future prediction errors and enhance subsequent learning (den Ouden et al., 2009).

These studies on prediction error in non-human animals and in human adults measured expectations about statistical contingencies learned over the course of an experimental session. However, very few studies have investigated the consequence of violations of core principles akin to what infants typically see in VOE experiments. One fMRI study with human adults found increased activation in DLPFC and ACC during events that violated fundamental physical relations (e.g., a magician closes his hand over a scarf and reveals that the scarf has disappeared) compared to events that did not violate any predictions (e.g., the scarf is still in the magician's hand), or events that were merely surprising due to their novelty (e.g., the magician puts the scarf in his mouth) (Parris, Kuhn, Mizon, Benattayallah, & Hodgson, 2009). Thus, it is possible to dissociate responses to impossible events from responses to novelty-related surprise. But it remains unknown whether these types of surprise reactions affect subsequent learning.

1.5. Children use prior knowledge for learning

Although the effect of violations of expectation on infants' learning remains unknown, older children can use prior knowledge to guide what they learn and how they explore. When three- to five-year-old children viewed an impossible solidity event in which a rotating screen appeared to pass through a block (akin to Baillargeon et al., 1985), they described the event as “magical” upon first observation. They also produced observable reactions to the surprising event, including gasps and stares at the apparatus.

After repeated viewings, however, children appealed to concrete explanations for the surprising event (e.g., that the block was crushed) and spontaneously explored the apparatus (Chandler & Lalonde, 1994).

A recent study asked how children's prior knowledge state influences their explanations and explorations of belief-violating events (Bonawitz, van Schijndel, Friel, & Schulz, 2012). Children were shown an asymmetrical object and a post, and were asked how the object should balance. One group incorrectly believed that the object should balance on its geometric center (Center theorists); another group correctly believed that the object should instead balance on its center of mass (Mass theorists). Children then viewed one of two types of apparatus: one in which an asymmetrical object balanced on its geometric center, or one in which the object balanced on its center of mass. They were given a choice to play with that very same apparatus, or an entirely novel toy. Children who saw the object balance in a way that was consistent with their beliefs (i.e., Center theorists who saw the object balance on its center, and Mass theorists who saw the object balance on its center of mass) opted to explore the novel toy. But, children who saw the object balance in a way that was inconsistent with their beliefs (i.e., Center theorists who saw it balance on its center of mass, and Mass theorists who saw it balance on its geometric center) preferentially explored that very apparatus over the novel toy. Moreover, children who had experienced evidence that violated their beliefs were more likely to appeal to a hidden cause for the surprising event (e.g., to suggest that a magnet was present). This finding shows that children can use their prior beliefs to mediate their exploration and explanations.

Other studies have demonstrated that children can use beliefs constructed on-line in the experimental session to drive their exploration and explanations (e.g., Schulz & Bonawitz, 2007; Legare, Gelman, & Wellman, 2010; Legare, 2012; van Schijndel, Visser, van Bers, & Raijmakers, 2015). In one such study, children were shown a novel object that, when placed on a box, always made the box light up; a different novel toy was always shown not to make the box light up. After children learned the effect (or lack of effect) of both kinds of toys, they were shown each toy placed on a separate box, with neither box lighting up. When asked by the experimenter, “Why did this happen?” children overwhelmingly chose to offer explanations for the event that was inconsistent with their new knowledge (i.e., children tried to explain why the toy that should have made the box light up did not work) (Legare et al., 2010). Not only were children motivated to explain the inconsistent event over the consistent event, they were more likely to explore the toys in ways that reflected their explanations. For instance, children who explained the inconsistent event using statements that appealed to causal explanations, like the toy or its batteries being broken, were more likely to test multiple hypotheses about the object’s failure. For example, they attempted to open the object to investigate it, or combined the broken object with a functioning one (Legare, 2012). Thus, children tested hypotheses for their explanations of events that violated their expectations.

However, it remains unknown whether much younger children – preverbal infants – also learn from and actively test hypotheses about events that violate prior knowledge. A plausible alternative is that verbal abilities, and prior experience receiving verbal explanations from adults, is necessary to spark this kind of inquiry. Still, there are a few

suggestive pieces of evidence that indeed infants might be motivated to learn from surprising events and/or test hypotheses for surprising events.

The first piece of evidence comes from research showing that infants can employ their prior knowledge to appropriately reason about object support relations. Infants younger than 12.5 months fail to take into account the proportional distribution of an asymmetrical object to determine whether it is adequately supported by a box underneath it, such that it will remain stable and not fall (Baillargeon, 1999). If, however, these infants see contrastive examples that highlight the relevant variable, they can successfully use proportional distribution information to reason about the object's behavior. Infants were shown two true examples: one in which the heavier half of an asymmetrical object rested on a box and the object did not fall, and one in which the lighter half of an asymmetrical object rested on the box and the object did fall. Following these teaching events, infants looked longer at surprising support events (i.e., at an asymmetrical object that should have fallen but did not) than non-surprising support events. Critically, infants who were taught with untrue events (i.e., in which the outcomes of the teaching events were reversed and defied principles of object support) did not successfully distinguish between adequate and inadequate support events at test (Baillargeon, 1999). These results suggest that infants integrated what they observed in the teaching events with their prior knowledge that unsupported objects should fall (e.g., Needham & Baillargeon, 1993) to learn to attend to the relevant variable of proportional distribution.

But do infants actually seek explanations for events that violate their expectations? In one study, 3.5-month-old infants showed no evidence of surprise when a toy that traveled behind a U-shaped occluder did not appear in the gap as it should

(Aguiar & Baillargeon, 2002). But further investigation of the source of this failure suggested that infants may have been so committed to principles of object behavior that they generated an explanation for the surprising event: that there must have been two identical objects, one behind each leg of the U-shaped occluder. When infants were first shown that there was only one toy on the stage before it was hidden, they indeed were surprised when the toy did not appear in the gap (Aguiar & Baillargeon, 2002).

Moreover, older infants intervene on novel toys in ways that depend on the evidence they have seen (Gweon & Schulz, 2011). Sixteen-month-olds who saw an adult successfully activate a toy, but failed to activate that same toy themselves, turned to their parent to intervene rather than choose to play with another toy. But when infants observed an adult successfully activate a toy and then they were given a different toy that did not activate, they were more likely to choose another toy with which to play. These findings suggest that infants rationally generated an appropriate explanation for why the toy failed to activate. What is more, infants integrated probabilistic information to determine whether their failure to activate the toy was attributable to themselves or to the object: if one experimenter successfully activated a toy twice, and another experimenter failed twice, infants who received the same inactive toy opted to change the agent (i.e., sought guidance from a parent) rather than the toy. But if infants saw two experimenters, each of whom succeeded in activating the toy once and failed once, they selectively changed the toy rather than seeking help from a parent. In both cases, infants saw only 50% success of activating the toy, but in the former case they appeared to generate the explanation that one agent was competent at activating the toy and the other not, and therefore that their own failure must be attributable to themselves. In the latter case, both

agents only succeeded 50% of the time, and therefore the toy must have been unreliable. This study suggests that infants can draw inferences using observed evidence to determine how best to interact with the world when entities fail to behave as expected.

The final piece of suggestive evidence that infants might be seeking explanations for surprising events comes from infants' social referencing behaviors. Infants are more likely look to their caregiver's face following events that violate expectations about object behavior than following events that accord with object behavior. It is possible that this increased social referencing behavior might reflect infants' attempts to resolve any uncertainties or seek information from a knowledgeable source (Walden et al., 2007).

Taken together, these experiments show that infants might be motivated to seek explanations for or information about events that are inconsistent with their expectations. However, no study has investigated whether *learning* is changed by having expectations violated. Here I tested the hypothesis that, early in life, violations of core expectations signal a special opportunity for learning. First I asked whether infants more effectively learn new information about objects that violated expectations than those that accorded with expectations (Experiments 1.1-1.3). Then I asked whether infants preferentially seek information from objects that violated expectations, and whether their exploratory actions test plausible explanations for an observed violation (Experiment 2). Finally, I asked whether surprise enhances learning in older children, outside of the controlled laboratory setting and in a more naturalistic learning environment (Experiments 3.1-3.4).

2. Question 1: Does detecting an unexpected event enhance infants' learning?

Given that infants have sophisticated core knowledge about objects (e.g., Baillargeon et al., 1985; Spelke et al., 1992; Spelke & Kinzler, 2007), I first asked whether they can harness this prior knowledge to guide subsequent learning. That is, I investigated whether witnessing a violation to core knowledge of object behavior enhanced infants' learning about the entities that behaved surprisingly. In Experiments 1.1-1.3 I showed infants an event whose outcome either was expected because it accorded with core knowledge of object behavior, or was surprising because it violated core knowledge, using events modeled on those in many previous studies (e.g., Spelke et al., 1992; Baillargeon, 1986; Wilcox et al., 1996). Then I taught infants something new about the object that had participated in the event, and, finally, measured how well they learned this new information.

Three aspects of the design were crucial. First, I ensured that events that violated core knowledge differed minimally from events that accorded with core knowledge, by perceptually matching the events in all respects except for their outcomes. Second, I ensured that any observed learning enhancement was caused by experiencing a violation of core expectations, rather than by longer perceptual exposure to objects that violated expectations, by matching the duration of infants' looking across outcome types. Third, I ensured that infants were learning something genuinely new by teaching them information that could not have been known beforehand, and that could not have been acquired just by seeing the objects themselves (i.e., I taught infants an object's hidden property).

Part of this chapter appears published as: “Stahl, A. E. & Feigenson, L. (2015). Observing the unexpected enhances infants’ learning and exploration. *Science*, 348, 91-94.”

2.1. Experiment 1.1 Infants’ learning following expected and unexpected events

In Experiment 1.1, 11-month-old infants saw an event that either accorded with or violated object solidity or spatiotemporal continuity, two core physical principles to which young infants have consistently shown sensitivity (e.g., Baillargeon, 1986; Spelke et al., 1992; Spelke et al., 1995; Wilcox et al., 1996). Infants then had the opportunity to learn new information about the object in the event, that it had a hidden auditory property (e.g., it squeaked). They were subsequently assessed on how well they learned the mapping between the object and the sound. Two different kinds of physical events were used in order to demonstrate that any obtained results were not specific to any particular kind of physical violation (e.g., an object passing through a wall).

Method

Solidity Condition

Participants. Twenty healthy full-term infants between 10.5 and 12 months old participated (range = 10 months, 19 days to 11 months, 24 days; mean = 11 months, 7 days; 12 females). Two additional infants were excluded for fussiness (1) or parental interference (1). Parents of all infants provided written informed consent prior to their participation.

Stimuli. Infants sat in a high chair in front of a stage; parents sat out of view. The stage (132 x 43 x 52.5 cm) had a concealed opening in its rear wall, a removable sloping ramp on its left side, and a track that ran across its width. A thin purple wall (1.5 x 28 x 27 cm) stood at the right-end of the track and a thicker purple wall (3 x 28 x 27 cm) could be placed across the track's path. A gray occluding screen (51 x 22 cm) was used to cover the right side of the stage during portions of the event; when the screen was in place, the purple wall(s) protruded 6 cm above it. A black curtain could be lowered to conceal the entire stage.

The stimulus objects were a green, yellow, and orange plastic car (approximately 17 x 13.5 cm) and a blue and red striped ball (7.5 cm diameter). For half of the infants the car was the target object and for the other half the ball was the target.

Procedure

Familiarization. Infants saw two identical familiarization trials. The curtain was raised to reveal the ramp at the left of the stage and the thin purple wall at the far right. The experimenter reached down and placed the gray screen onstage, covering the stage's right half. The top of the purple wall protruded above the screen. Next the experimenter reached in from above, holding the target object (e.g., car), and released it at the top of the ramp. The object rolled down the ramp, across the stage, and passed behind the occluding screen. Finally, the experimenter lifted the screen to reveal the object at the stage's far right, where it had been stopped by the thin purple wall. The object remained there for 5 s, after which the curtain was lowered to cover the stage.

Solidity Event. Next, infants saw a single solidity event. The curtain was raised to reveal the ramp on the left and the thin purple wall on the far right. The experimenter

reached in from above and showed infants the thicker purple wall, twisting and knocking on it to show that it was solid before placing it across the center of the track. She then put the screen in place, covering the right half of the stage and hiding both walls except for their tops. The experimenter then said, “Look! Look at this! Watch this,” as she reached in with the target object (e.g., the car) and released it at the top of the ramp. The object rolled down the ramp, across the stage, and disappeared behind the screen. The experimenter then lifted the screen to reveal either that the object appeared to have been stopped by the thick wall and come to rest near the center of the stage, thereby according with expectations about solidity (Expected solidity event, $n=10$), or that the object appeared to have passed through the thick wall and come to rest at the far right side of the stage, thereby violating expectations about solidity (Violation solidity event, $n=10$) (Figure 1). Unlike previous studies designed to measure differences in infants’ looking to expected versus violation events, here I gave all infants the same limited visual exposure to the Expected and Violation outcomes; all infants had just 10 s to encode the event outcome.

Teaching Event. After 10 s the experimenter demonstrated that the target object had a hidden auditory property. She grasped the object from its outcome position and moved it up and down rhythmically for 12 s while a sound (e.g., squeaking) played from a hidden central location (Figure 1). Half the infants were taught that the target object made a squeaking sound, and half were taught that it made a ringing sound; this was fully crossed with the target object’s identity (car versus ball). If infants looked away during these 12 s, the experimenter attracted infants’ attention and only resumed when they re-

attended. After 12 s of exposure to the auditory property, the curtain was lowered to cover the stage.

Test. Infants' learning was assessed in a single test trial (Figure 1). The curtain was raised to reveal an empty stage. The experimenter reached down and simultaneously placed two objects on the stage 70 cm apart: the target object from the preceding event (e.g., car) and a new distractor object (e.g., ball). These rested silently for 5 s (Baseline). Then the experimenter grasped both objects and moved them up and down rhythmically while the same sound that had played during the Teaching Event played for 10 s from a hidden central location (Mapping Test). Whether the target object was on the left or right side was counterbalanced across infants.

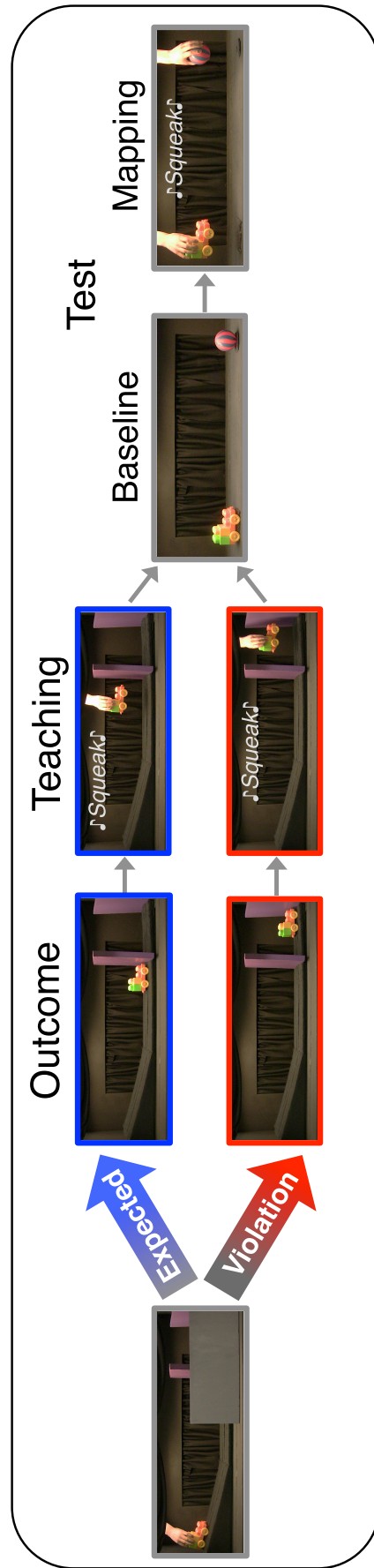


Figure 1. Event sequence for the Solidity condition of Experiment 1.1. Infants saw an object (e.g., car) roll across a stage and behind an occluding screen. The screen was lifted to reveal either that the car was stopped by the wall (Expected outcome), or that the car appeared to pass through the wall (Violation outcome). All infants were then taught that the object produced a particular sound (e.g., squeaking) when lifted up and down. Finally, infants were tested on whether they learned this new information. Infants first saw the object from the event (car) paired with a new object (e.g., ball) resting on the stage in silence (Baseline). Next, they saw those objects lifted up and down while the same squeaking sound played (Mapping).

Spatiotemporal Continuity Condition

Participants. Twenty healthy full-term infants between 10.5 and 12 months old participated (range = 10 months, 15 days – 11 months, 26 days; mean = 10 months, 30 days; 13 females). Four additional infants were excluded for sibling interference (1), inattentiveness (1), or experimenter error (2).

Stimuli. Two identical black foam-core screens (27 x 29 cm) were used to hide the objects. Each had a concealed rear compartment that allowed the experimenter to surreptitiously add or remove objects from the stage.

The stimulus objects were a green and red spotted ball (7.5 cm diameter) and a blue block with a schematic face (6 x 10 x 6 cm). For half the infants the ball was the target object and for the other half the block was the target.

Procedure

Familiarization. Infants saw two identical familiarization trials. The experimenter placed a screen in the center of the empty stage. She waved the target object (e.g., ball), then held it directly above the screen. She said, “Watch this!” and placed the object behind the screen. She immediately lifted the screen to reveal the object resting on the stage. After 5 s the curtain was lowered to cover the stage.

Continuity Event. Next, infants saw a single continuity event. The curtain was raised to reveal an empty stage. The experimenter placed the two identical screens on stage 27 cm apart, wiggling them to show that they were unconnected. She waved the target object in front of the left screen, saying, “Look! Look at this! Watch this,” then hid it behind the left screen. The experimenter then lifted both screens simultaneously to reveal either that the target object was still behind the left screen, thereby according with

expectations about continuity (Expected continuity event, $n=10$), or that it was now behind the right screen, thereby violating expectations about continuity (Violation continuity event, $n=10$) (Figure 2). Infants were given 10 s to look at the event outcome.

Teaching Event. The Teaching Event was nearly identical to that following the Solidity events: after 10 s the experimenter grasped the target object from its outcome position and moved it up and down while a sound played from a hidden central location (Figure 2). Half the infants were taught that the target object made a squeaking sound, and half were taught that it made a rattling sound—this was fully crossed with the target object's identity (ball versus block).

Test. Infants saw the curtain raised to reveal an empty stage. The experimenter reached down and simultaneously placed two objects on stage 70 cm apart: the target object (e.g., ball) and a new distractor object (e.g., block). These rested silently for 5 s (Baseline). Then the experimenter grasped both objects and moved them up and down rhythmically while the same sound that had played during the Teaching Event played for 10 s from a hidden central location (Mapping Test) (Figure 2). Whether the target object was on the left or right side was counterbalanced across infants.

Infants' looking was coded offline, frame-by-frame, by a trained observer who was blind to experimental condition. A second observer recoded 20% of all testing sessions in Experiments 1.1-1.3; coder agreement averaged 0.98.

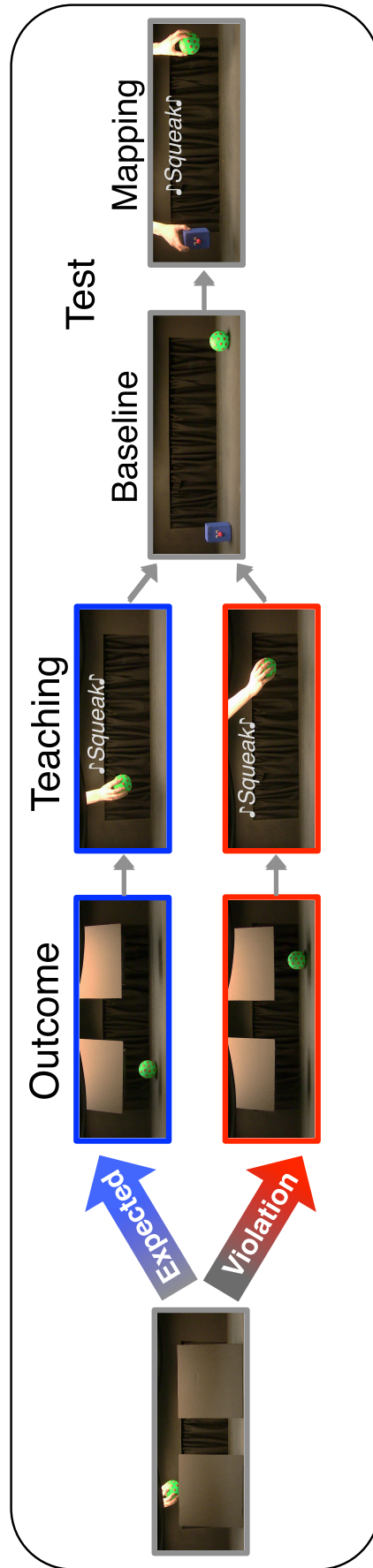


Figure 2. Event sequence for the Continuity condition of Experiment 1.1. Infants saw an object (e.g., ball) hidden behind one of two screens. The screens were lifted to reveal either that the ball was behind the same screen (Expected outcome), or that the ball was behind the other screen (Violation outcome). All infants were then taught that the object produced a particular sound (e.g., squeaking) when lifted up and down. Finally, infants were tested on whether they learned this new information. Infants first saw the object from the event (ball) paired with a new object (e.g., block) resting on the stage in silence (Baseline). Next, they saw those objects lifted up and down while the same squeaking sound played (Mapping).

Results

Event outcome. I first analyzed infants' looking to the outcomes of the Solidity and Continuity events (Figure 3), prior to the Teaching Event. Infants in the Solidity condition looked for an average of 6.33 s at the Expected outcome (SD=2.33 s) and 5.29 s at the Violation outcome (SD=2.05 s). Infants in the Spatiotemporal Continuity condition looked for an average of 3.19 s at the Expected outcome (SD = 1.80 s) and 4.29 s at the Violation outcome (SD=1.99 s). A univariate ANOVA with outcome looking time as the dependent variable and event type (Solidity or Continuity) and outcome type (Expected or Violation) as fixed factors revealed a main effect of event type, $F(1,36)=10.159$, $P=0.003$, partial $\eta^2=0.22$, with infants looking longer at outcomes of Solidity events ($M=5.81$ s, $SD=2.20$ s) than Continuity events ($M=3.74$ s, $SD=1.93$ s). Critically, there was no main effect of outcome type, $F(1,36)=0.002$, $P=0.96$; this was as predicted since I limited the time infants had to view these outcomes. Thus any subsequent differences in learning cannot be attributed to longer perceptual exposure to the object in the Violation events.

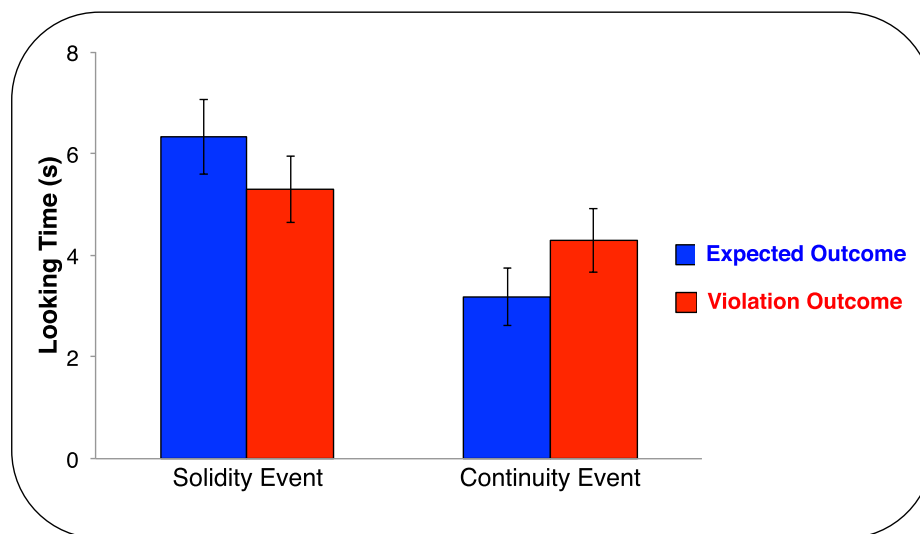


Figure 3. Infants' looking times to the Expected and Violation outcomes of the Solidity and Continuity events of Experiment 1.1.

Test trial. For each infant I calculated a learning score by subtracting the proportion of time infants looked at the target object relative to the new distractor object during the Baseline from the proportion they looked at the target object during the Mapping Test. If infants had successfully learned the object-sound mapping, they should increase the proportion of time they looked at the target object when the sound played – such auditory-visual “matching” is the pattern typically observed in studies of infants’ mapping abilities (e.g., Kuhl & Meltzoff, 1984).

I found that infants’ learning of the object-sound mapping depended on whether they had just seen an Expected or Violation event. A univariate ANOVA with learning score as the dependent variable and event type (Solidity or Continuity) and outcome type (Expected or Violation) as fixed factors yielded only a significant main effect of outcome type, $F(1,36)=10.691$, $P=0.002$, partial $\eta^2=0.229$. Infants’ learning scores were significantly greater following Violation than Expected events (Figure 4A). I then compared infants’ learning scores to chance (zero). I found that these were no different from chance following events that accorded with object Solidity ($M=-0.10$, $SD=0.29$), $t(9)=-1.088$, $P=0.31$, or Continuity ($M=0.06$, $SD=0.12$), $t(9)=1.62$, $P=0.14$. However, learning scores were significantly greater than chance following violations to both object Solidity ($M=0.17$, $SD=0.18$), $t(9)=3.092$, $P=0.01$, and Continuity ($M=0.20$, $SD=0.17$), $t(9)=3.715$, $P=0.005$ (Figure 4A).

A. Infant learning following:

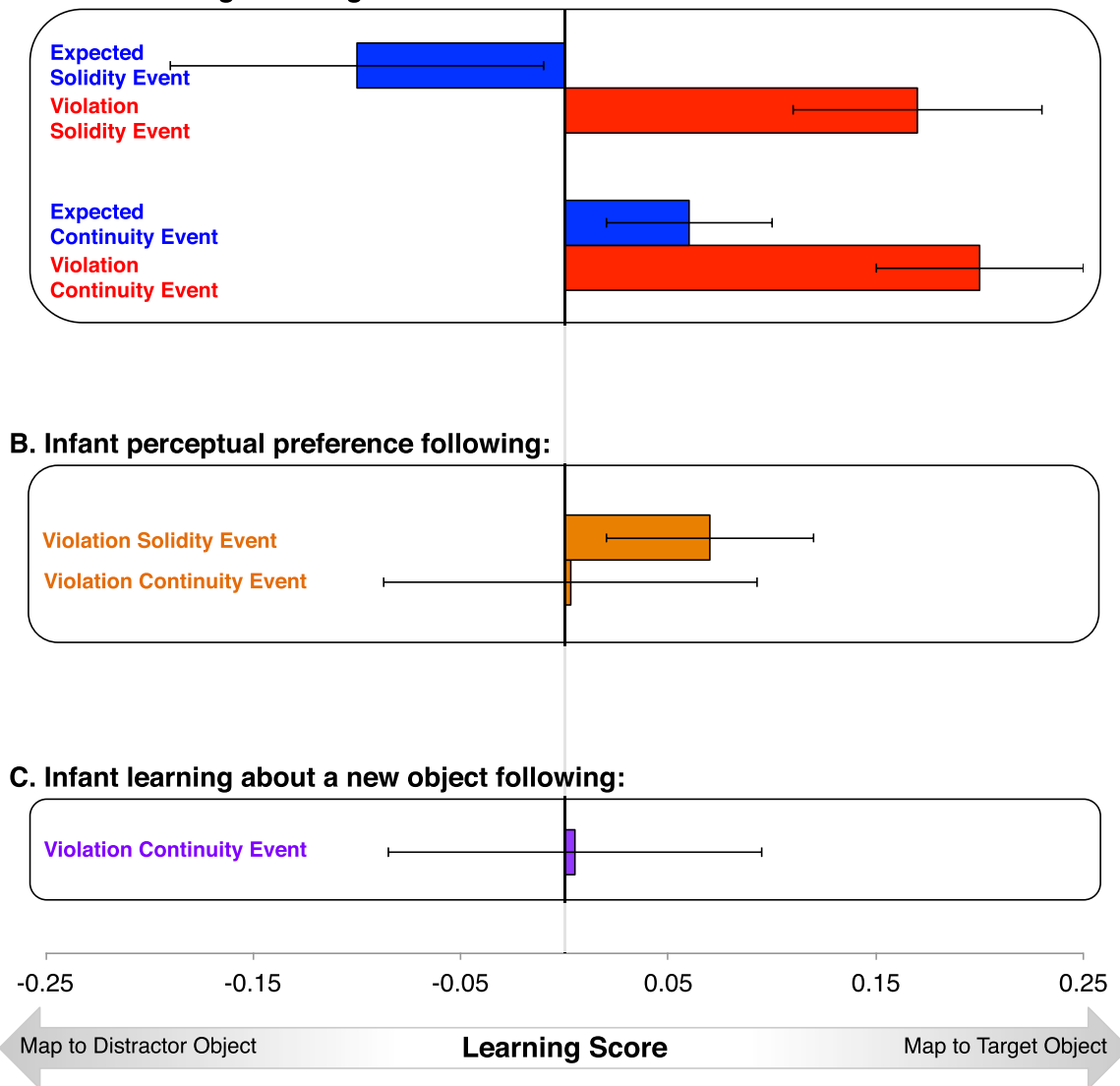


Figure 4. Results from Experiments 1.1-1.3. Bars represent learning scores (proportion of looking to target object during Mapping minus proportion of looking to target object during Baseline). Error bars represent standard error of the mean. A. Infants' learning following Expected and Violation events in Experiment 1.1. B. Infants' perceptual preference for the target object following Violation events in Experiment 1.2. C. Infants' learning about an entirely novel object following a Violation event in Experiment 1.3.

2.2. Experiment 1.2 Ruling out perceptual preference for surprising objects

In Experiment 1.2 I asked whether this pattern reflected actual learning, or just greater attention to objects that had violated expectations. That is, it is possible that

infants from Experiment 1.1 looked longer to the correct object during the Mapping test simply because they had a preference for the object that violated their expectations, and they did not actually learn the mapping between that object and the sound.

Method

Solidity Condition

Participants. Ten healthy full-term infants between 10.5 and 12 months old participated (range = 10 months, 26 days – 11 months, 24 days; mean = 11 months, 9 days; 6 females). Three additional infants were excluded for fussiness (2) or experimenter error (1).

Stimuli. The stimuli were identical to those in the Solidity condition of Experiment 1.1.

Procedure. The procedure was identical to that in the Violation solidity event of Experiment 1.1, with one exception. During the Mapping Test, infants heard a novel sound. Half the infants were taught that the object made a squeaking sound during the Teaching Event, but heard a ringing sound during the Mapping Test, and half experienced the reverse.

Spatiotemporal Continuity Condition

Participants. Ten healthy full-term infants between 10.5 and 12 months old participated (range = 10 months, 18 days – 11 months, 28 days; mean = 11 months, 6 days; 6 females). Three additional infants were excluded for inattentiveness (1) or experimenter error (2).

Stimuli. The stimuli were identical to those in the Continuity condition of Experiment 1.1.

Procedure. The procedure was identical to that in the Violation continuity event of Experiment 1.1, with one exception. During the Mapping Test, infants heard a novel sound. Half the infants were taught that the object made a squeaking sound during the Teaching Event, but heard a rattling sound during the Mapping Test, and half experienced the reverse.

Results

A univariate ANOVA with learning score as the dependent variable and event type (Solidity or Continuity) and sound type (taught sound from the Violation conditions of Experiment 1.1 or novel sound from Experiment 1.2) as fixed factors yielded only a significant main effect of sound type. Infants' learning scores were significantly greater when the taught sound played in the Mapping Test (Experiment 1.1) than when the novel sound played, $F(1,36)=5.349$, $P=0.03$, partial $\eta^2=0.129$. When a novel sound was played during the Mapping Test, infants' learning scores were not significantly above chance following violations to object Solidity ($M=0.07$; $SD=0.15$), $t(9)=1.453$, $P=0.18$, or Continuity ($M=0.003$, $SD=0.29$), $t(9)=0.036$, $P=0.97$ (Figure 4B). These results confirm that infants' performance in Experiment 1.1 reflected successful learning of an object property, rather than heightened visual preference for an object that had violated expectations.

Infants' greater learning scores in the Violation conditions of Experiment 1.1 cannot be attributed to those infants having had more perceptual exposure to the target

object (as compared to infants in Experiment 1.2). A univariate ANOVA with looking time to the event outcome as the dependent variable and event type (Solidity or Continuity) and sound type (taught sound from Experiment 1.1 or novel sound from Experiment 1.2) yielded a main effect of sound type, $F(1,36)=4.452$, $P=0.042$, $\eta^2=0.11$. Infants in Experiment 1.2 (who heard the novel sound at test) looked longer following violations to object Solidity ($M=6.79$, $SD=1.93$) and Continuity ($M=5.81$, $SD=2.93$) than did infants in Experiment 1.1.

2.3. Experiment 1.3 Infants' learning about new objects following unexpected events

Finally, in Experiment 1.3, I asked whether violations of expectation enhance learning specifically about objects that violated expectations, or about anything following a violation. Infants who witness a surprising event might experience heightened attention or arousal that might enhance learning in a diffuse way. Alternatively, infants' learning might be beneficially constrained to the very object that violated their expectations, and not to entities that are irrelevant to the observed violation.

Method

Participants. Ten healthy full-term infants between 10.5 and 12 months old participated (range = range = 10 months, 28 days – 12 months, 0 days; mean = 11 months, 5 days; 5 females). Three additional infants were excluded for parental interference (1) or experimenter error (2).

Stimuli. The stimuli were the ball and block from the Experiment 1.1 Continuity event and the car from the Experiment 1.1 Solidity event.

Procedure. The procedure was identical to that in the Violation continuity event of Experiment 1.1, with two exceptions. After the Violation outcome was revealed (i.e., after the ball that had been hidden behind the left screen was revealed behind the right screen), the ball remained in place on the stage floor. After 10 s the experimenter reached in with a novel object (i.e., block) and moved it up and down rhythmically in the center of the stage for 12 s while either the squeaking or rattling sound played from a hidden central location (Teaching Event). As in the other experiments, the experimenter ensured that infants were attending to this object during the demonstration of the auditory property.

During the Baseline, half the infants saw the block paired with the target object that had participated in the Continuity event (i.e., ball), and the other half saw the block paired with an entirely new distractor object (i.e., car) – these sat on stage silently for 5 s. After 5 s, the experimenter reached in and moved both objects up and down rhythmically while the sound that infants had heard during the Teaching Event (either squeaking or rattling) played from a hidden central location for 10 s (Mapping Test). Infants' subsequent learning scores did not differ depending on whether the block was paired with the ball or the car ($P=0.69$).

Results

When infants were taught about a novel, unrelated object following a Violation continuity event, their learning scores did not differ from chance ($M=0.005$, $SD=0.23$), $t(9)=0.074$, $P=0.94$. Infants' learning scores were significantly greater when they had been taught about the object that had violated their expectations (Experiment 1.1) than

when taught about an unrelated novel object (Experiment 1.3), $t(18)=2.126$, $P=0.048$ (Figure 4C). Hence violations of expectation enhanced learning only for the object involved in the violation event, not for unrelated objects.

Infants' greater learning scores in the Violation conditions of Experiment 1.1 cannot be attributed to those infants having had more perceptual exposure to the target object (as compared to infants in Experiment 1.3). An independent samples t-test found that infants' looking to the Violation continuity event outcome in Experiment 1.3 ($M=3.45$, $SD=1.76$) did not differ from that of Experiment 1.1, $t(18)=1.0$, $P=0.33$.

2.4 General discussion of Experiments 1.1-1.3

Experiment 1.1 showed that infants learn more effectively following events that violate their expectations than following events that accord with their expectations. Infants efficiently learned an objects' hidden auditory property when that object violated the principles of object solidity or continuity, but failed to show any evidence of learning following a perceptually similar event that violated no expectations. Previous studies have shown that infants ranging from a few hours to 16 months old can learn associations between objects, sounds, locations, functions, words, and nonobvious properties (e.g., Morrongiello, Fenwick, & Chance, 1998; Richardson & Kirkham, 2004; Perone & Oakes, 2002; Werker, Cohen, Lloyd, Casasola, & Stager 1998; Welder & Graham, 2001). These previous studies taught infants arbitrary pairings over periods of repeated exposure. In contrast, infants in the present study robustly learned object-sound mappings in a single trial, with no habituation or familiarization – but only when taught about an object that had violated their expectations. Importantly, this learning enhancement was not observed

for one particular kind of physical violation. Infants showed elevated learning following violations to both solidity and spatiotemporal continuity.

Experiment 1.2 ruled out the possibility that this enhanced learning might reflect increased interest in the object that behaved surprisingly, rather than actual learning about this object. When infants saw a surprising event and were taught that the object produced a particular sound (e.g., squeaking), they did not look at that object during the test when a novel sound (e.g., rattling) played, suggesting that they did not simply prefer to look at the object that surprised them. Instead, infants had apparently acquired genuinely new information about objects that violated their expectations.

Finally, Experiment 1.3 demonstrated that infants' enhanced learning is constrained. Infants did not show any evidence of learning about an irrelevant object that was presented immediately after a surprising event, indicating that enhanced learning following surprising events cannot be attributed to an overall increase in attention or arousal that would induce learning in a diffuse way. Infants' failure to learn about this novel object shows that the learning enhancement observed in Experiment 1.1 also was not due to general novelty. When taught about an object that was completely perceptually novel (because it had never been seen before) but did not violate any expectations, infants showed no evidence of learning.

3. Question 2: Do infants selectively explore and seek explanations about objects that behaved surprisingly?

The finding that violations shaped infants' learning in a targeted way, enhancing learning only about objects relevant to the observed violation, raises a further question

about the nature of the new information learned. In Experiment Series 1, the new information taught to infants was arbitrary in the sense that it did not clearly causally relate to the surprising violations (because the sound made by an object does not offer a direct explanation for its behavior). Besides enhancing learning for such arbitrary mappings (like those acquired by non-human animals; e.g., Pearce & Hall, 1980), do violations of expectation privilege the learning of particular kinds of information – ones that are relevant to the nature of the surprising event? When an observation conflicts with prior knowledge, an effective learning strategy would be to seek evidence that could explain the discrepancy between what was predicted and what was observed. Older children engage in this kind of hypothesis testing, performing targeted actions to support or rule out possible explanations for an event (Bonawitz et al., 2012; Legare, 2012). For example, when a toy does not behave as expected, children often offer an explanation (e.g., reporting that it is missing batteries) and test this hypothesis (e.g., by opening the object) (Legare, 2012). But it is unknown whether preverbal infants actively test hypotheses about events, especially events involving violations of core knowledge.

Part of this chapter appears published as: “Stahl, A. E. & Feigenson, L. (2015). Observing the unexpected enhances infants’ learning and exploration. *Science*, 348, 91-94.”

3.1. Experiment 2 Infants’ exploration following expected and unexpected events

Experiment 2 had two goals. The first goal was to ask whether infants preferentially seek information from (i.e., would prefer to play with and explore) an object that violated expectations over an object that did not. The second goal of

Experiment 2 was to ask whether infants actively seek explanations for the surprising events. Infants saw an event that either accorded with or violated the principles of object solidity or (extending my inquiry to another principle of object behavior) object support. Infants as young as 3 months old expect that an object should be supported when it is in full contact with a platform underneath it, and they expect the object to fall when it is pushed completely beyond the surface of the platform (Baillargeon et al., 1992; Needham & Baillargeon, 1993). Therefore, half of the infants in Experiment 2 saw a support event that either culminated in an expected outcome (target object remains fully supported by the surface underneath) or a violation outcome (target object loses contact with supporting surface, but fails to fall).

In Experiment 2, no properties were taught to infants following either the expected or surprising solidity and support events. Instead, immediately following the events the experimenter placed two objects on the infants' high chair tray – the target object from the preceding expected or surprising event, and a novel distractor object. I asked which object infants would choose to play with, and what kind of exploratory actions they engaged in. If an observer sees an object violate solidity (i.e., a ball passes through a wall), an effective strategy to seek an explanation for this behavior would be to test its solidity by banging it on a solid surface. But if an observer sees a support violation (i.e., a ball floats in mid-air), an effective strategy to test its support would not be to bang the object, but rather to drop it. Here I examined whether infants' exploratory actions tested hypotheses about the particular kind of violation seen.

Method

Solidity Condition

Participants. Twenty healthy full-term infants between 10.5 and 12 months old participated (range = 10 months, 15 days – 11 months, 28 days; mean = 11 months, 4 days; 8 females). Nine additional infants were excluded for fussiness (2), parental interference (4), experimenter error (1), equipment failure (1), or refusal to engage with the objects (1).

Stimuli. The stimuli were identical to those in the Solidity event of Experiment 1.1. For half the infants the toy car was the target object, and for the other half the ball was the target.

Procedure. The Familiarization and Solidity event were identical to those in Experiment 1.1. Half the infants saw the Expected solidity event, in which a ball or car rolled down a ramp and was revealed to have been stopped by a solid wall in its path. The other infants saw the Violation solidity event, in which the ball or car rolled down the ramp and was revealed to have apparently passed through the solid wall (Figure 5). Following the event, the target object remained visible in its revealed position for 10 s before the curtain was lowered over the stage. Infants were not taught any properties of the object.

Exploration Period. After the curtain was lowered, the experimenter emerged from behind the stage and placed two objects on either side of the infants' high chair tray: the ball and the car (which of these had served as the target object from the preceding solidity event was counterbalanced across infants; Figure 5). Whether the target object was placed on the left or right side was also counterbalanced across infants. The

experimenter did not look at or engage infants while placing the objects; instead she immediately stepped out of view and gave infants 60 s to freely explore the two objects. If either object went out of infants' reach (e.g., by falling on the floor), the experimenter immediately retrieved it and placed back it on the tray. No objects made any sound.

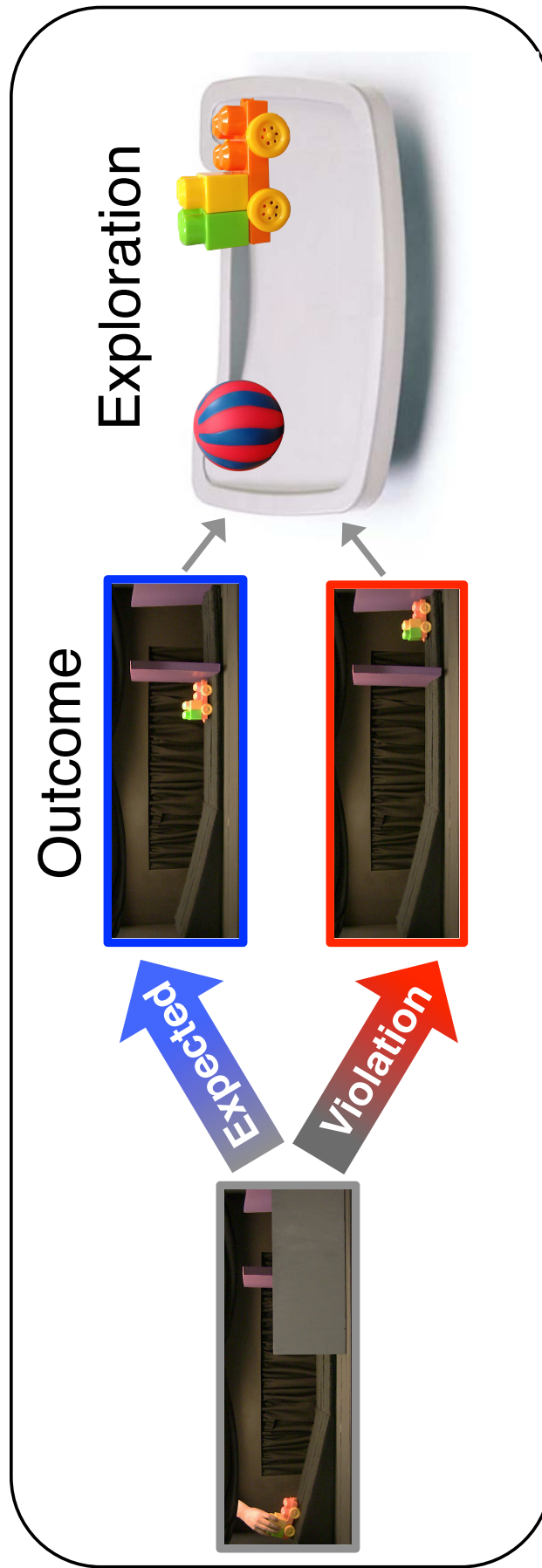


Figure 5. Infants saw the same Expected or Violation outcomes to the solidity event as in Experiment 1.1. They were then given two objects to freely explore for 60 seconds: the target object from the event (e.g., car), and a new distractor object (e.g., ball).

Support Condition

Participants. Twenty healthy full-term infants between 10.5 and 12 months old participated (range = 10 months, 17 days – 12 months, 4 days; mean = 11 months, 7 days; 7 females). Two additional infants were excluded for sleepiness (1) or parental interference (1).

Stimuli. A white and gray horizontally striped box (33 x 20.5 x 10 cm) rested on the left side of the stage. The stimulus objects were the car and ball from the Solidity condition; which of these served as the target object was counterbalanced across infants.

Procedure.

The support condition was based on the procedure used by Needham and Baillargeon (1993).

Familiarization. Infants saw two identical familiarization trials designed to familiarize infants with the target object and experimental apparatus. The curtain was raised to reveal the target object (e.g., car) resting on top of the striped box. The experimenter immediately reached into the stage and used her index finger to slowly push the object 8 cm to the center of the box, then removed her hand from the stage while leaving the object in place. After 5 s, the curtain was lowered over the stage.

Support Event. Next, infants saw a single support event. The curtain was raised to reveal the target object resting on the box. For infants who saw the Expected event, the experimenter said, “Look! Look at this! Watch this,” and then slowly pushed the object from the left side of the box 16 cm to the box’s edge, so that it remained completely supported by the box throughout. For infants who saw the Violation event, the target object started in the center of the box, and the experimenter slowly pushed it 16 cm, over

the box's edge so that it no longer had any contact with the box and appeared to float in mid-air (Figure 6). Infants had 10 s to look at the event outcome (for infants in the Expected condition: the target object resting on the box's surface; for infants in the Violation condition: the target object "floating" in mid-air).

Exploration Period. The Exploration Period was exactly as in the Solidity condition (Figure 6).

Coding.

Exploration. Infants' exploration was coded in terms of their looking and touching behaviors during the 60-second exploration period. Looking was coded as directed at the target object, the distractor object, or neither. Touching was coded as directed at the target object, the distractor object, both (because it was possible to hold an object in each hand), or neither. Infants were only coded as touching an object if contact with the object appeared to be intentional (e.g., an elbow grazing an object did not count). All exploratory behaviors were coded offline, frame-by-frame, by a trained observer who did not know whether infants had seen an Expected or Violation event, and who was unaware which object was the target. A second observer recoded all sessions and coder agreement averaged 0.97.

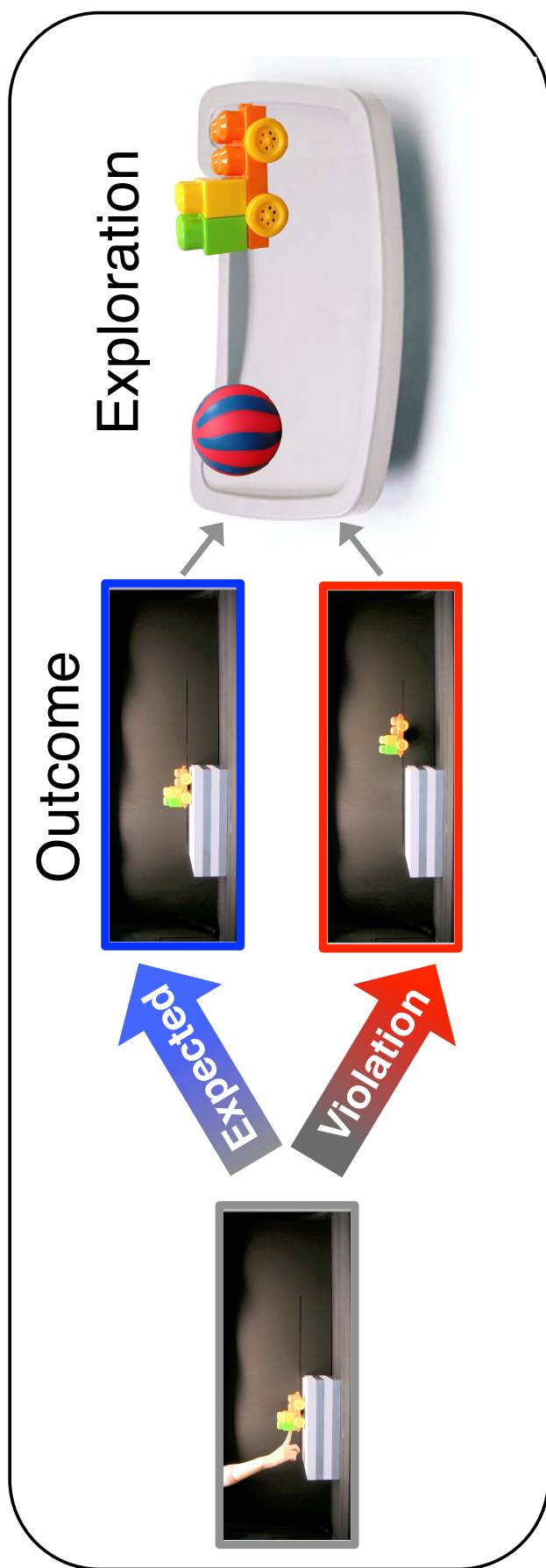


Figure 6. Infants saw a target object (e.g., car) pushed along the surface of a box. The car was either pushed to the surface edge, but remained completely supported (Expected outcome), or was pushed over the surface edge but did not fall (Violation outcome). Infants were then given two objects to freely explore for 60 seconds: the target object from the preceding event (e.g., car), and a new distractor object (e.g., ball).

Action Tendencies. Because details of infants' exploratory behaviors might reveal an even richer interplay between knowledge and exploration, I also examined whether infants explored the target object qualitatively differently depending on which violation they had seen. I analyzed two common exploratory behaviors, each relevant to one of the presented events: banging an object (relevant to testing object solidity), and dropping an object onto the table or floor (relevant to testing object support). An action was coded as banging if infants intentionally brought an object into abrupt contact with any other surface (the tray, themselves, or the other object), or if they brought their hand into abrupt contact with the object. An action was coded as dropping if infants intentionally released an unsupported object onto the floor or onto the high chair tray, or if they intentionally pushed the object off the tray surface. An object accidentally falling off the tray (e.g., by rolling during play) did not qualify. An observer who did not know whether infants had seen an Expected or Violation event, and who was unaware which object was the target, coded all behaviors. A second observer recoded all sessions and coder agreement averaged 0.98 for banging and 0.98 for dropping.

Results

Event Outcome. Before examining exploratory behavior, I first analyzed infants' looking times to the Solidity and Support event outcomes (Figure 7), prior to the Exploration Period, in order to ensure that any subsequent differences in infants' exploratory behavior were not caused by differences in perceptual exposure to the target object following Expected versus Violation outcomes. In the solidity condition, infants looked for 4.37 s at the Expected event outcome ($SD=2.12$ s) and 4.41 s at the Violation

event outcome (SD=1.73 s). In the support condition, infants looked 4.49 s at the Expected event outcome (SD = 2.01 s) and 5.59 s at the Violation event outcome (SD=2.20 s). A univariate ANOVA with looking time as the dependent variable and event type (Solidity or Support) and outcome type (Expected or Violation) as fixed factors showed no main effect of outcome type, $F(1,36)=0.794$, $P=0.379$, and no interactions. Thus, infants had equivalent perceptual exposure to the objects after both event types and both outcome types.

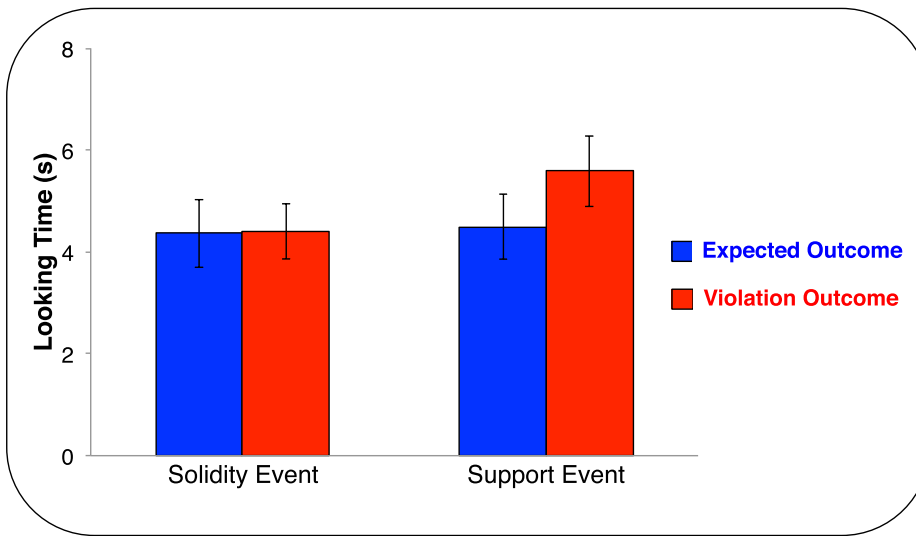


Figure 7. Infants' looking times to the Expected and Violation outcomes of the Solidity and Support events of Experiment 2.

Exploration Preference. Next I analyzed how long infants spent exploring (looking at and/or touching) the target object versus the new distractor object during the Exploration Period. I calculated infants' preference to explore the target object versus the new distractor object by subtracting the amount of time infants explored the distractor object from the amount of time they explored the target object; this yielded an exploration preference score for each infant. A univariate ANOVA with exploration preference score as the dependent variable and event type (Solidity or Support) and

outcome type (Expected or Violation) as fixed factors yielded a significant main effect of outcome type, $F(1,36)=5.933$, $P=0.02$, partial $\eta^2=0.14$; infants who had seen a Violation event showed a greater preference to explore the target object than infants who had seen the Expected event. I next compared infants' exploration preference scores to chance (i.e., no difference in preference for the target or distractor object). Across Expected solidity (M=-18.87, SD=32.20) and support (M=2.80; SD=29.08) events, infants' exploration scores did not differ from chance, indicating that they explored the objects equally, $t(19)=-1.128$, $P=0.27$. In contrast, across Violation solidity (M=16.98, SD=27.96) and support (M=11.85, SD=27.09) events, infants' exploration scores were significantly above chance; infants spent significantly longer exploring the target object than the distractor object, $t(19)=2.395$, $P=0.027$ (Figure 8).

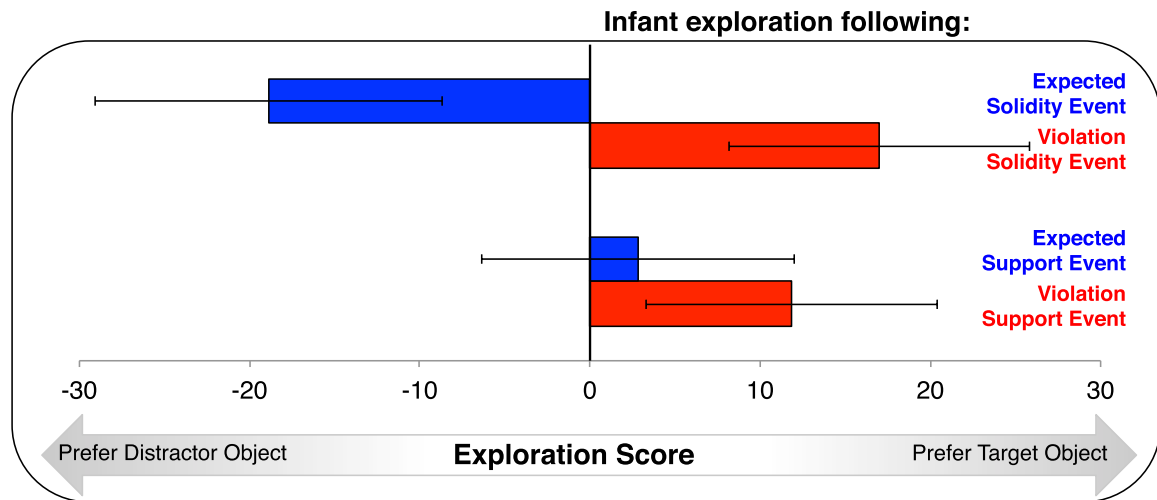


Figure 8. Infants' exploration scores following Expected and Violation events in Experiment 2. Bars represent looking at and/or touching the target object minus looking at and/or touching the distractor object. Error bars represent standard error of the mean.

Action Tendencies. First I measured the frequency of infants' banging and dropping of the target object. Because more instances of object banging can occur within a given time period than can instances of object dropping, I converted the frequencies of

these behaviors into z-scores to empower their direct comparison. I calculated z-scores for each behavior separately, using the averages and standard deviations of banging ($M=1.73$, $SD=2.61$) and dropping ($M=0.58$, $SD=1.26$) performed on the target object by all infants. I then calculated an action tendency score by subtracting the z-scored frequency of infants' object dropping from the z-scored frequency of their object banging. A univariate ANOVA with action tendency score as the dependent variable and event type (Solidity or Support) and outcome type (Expected or Violation) as fixed factors yielded a significant interaction between event type and outcome type, $F(1,36)=9.43$, $P=0.004$, partial $\eta^2=0.208$. An independent samples t-test revealed that infants who had seen an object appear to pass through a wall (Violation solidity event) banged that object more than they dropped it ($M=0.97$, $SD=1.57$), relative to infants who had seen the same object stopped by the wall (Expected solidity event) ($M=-0.29$, $SD=0.60$), $t(18)=2.378$, $P=0.029$. In contrast, infants who had seen an object appear to hover in mid-air (Violation support event) did the reverse: they dropped the object more than they banged it ($M=-1.05$, $SD=1.96$), relative to infants who had seen the same object fully supported (Expected support event) ($M=0.37$, $SD=0.96$), $t(18)=-2.045$, $P=0.056$ (Figure 9).

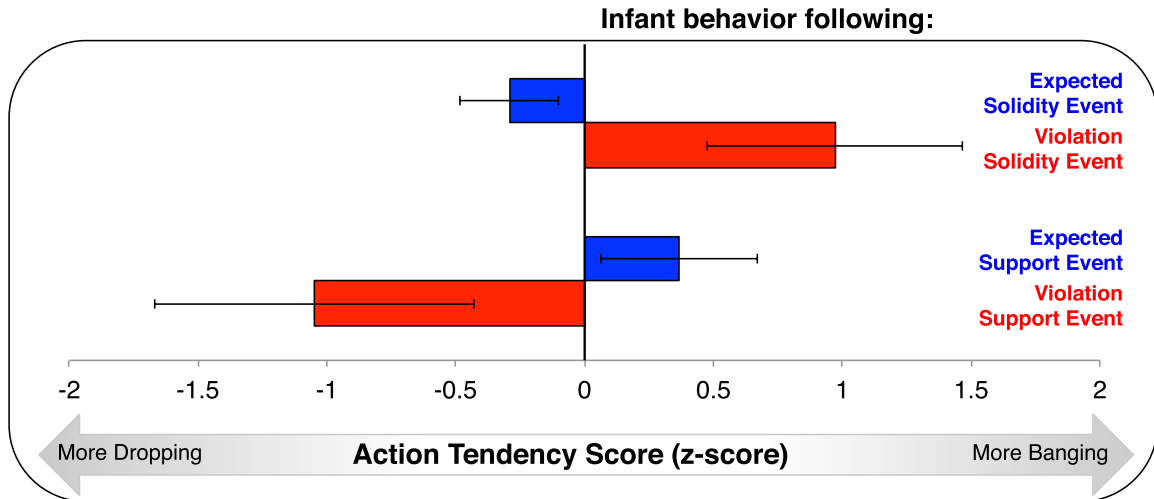


Figure 9. Infants' action tendency scores on the target object following Expected and Violation events in Experiment 2. Bars represent infants' z-scored object banging behaviors minus z-scored object dropping behaviors. Error bars represent standard error of the mean.

Finally, I examined infants' banging and dropping of the new distractor object that had not participated in the solidity or support event. I calculated z-scores for each behavior separately, using the averages and standard deviations of banging ($M=1.85$, $SD=4.63$) and dropping ($M=0.90$, $SD=1.96$) on the distractor object for all infants. As with the target object, I calculated action tendency scores by subtracting the z-scored frequency of infants' object dropping from the z-scored frequency of their object banging, this time on the distractor object. A univariate ANOVA with action tendency score on the distractor object as the dependent variable and event type (Solidity or Support) and outcome type (Expected or Violation) as fixed factors yielded a main effect of event type, $F(1,36)=4.574$, $P=0.04$, partial $\eta^2=0.11$. Critically, there was no significant interaction between event type and outcome type, $F(1,36)=0.062$, $P=0.80$. Infants did not act differentially on an object that had not participated in the preceding event, regardless of whether that event involved an Expected outcome of a solidity event ($M=0.39$, $SD=1.60$), an Expected outcome of a support event ($M=-0.48$, $SD=1.57$), a Violation outcome of a

solidity event ($M=0.60$, $SD=1.52$), or a Violation outcome of a support event ($M=-0.51$, $SD=1.13$).

A repeated measures ANOVA with action tendency score as the dependent variable, object type (target or distractor) as the within-subjects factor, and event type (Solidity or Support) and outcome type (Expected or Violation) as between-subjects factors yielded a significant main effect of event type, $F(1,36)=5.502$, $P=0.03$, $\eta^2=0.133$ – overall, infants who saw a solidity event banged more, whereas infants who saw a support event dropped more. The analysis also yielded a significant interaction between event type and outcome type, $F(1,36)=4.172$, $P=0.048$, $\eta^2=0.104$. Infants who saw the Expected events did not differentially engage with the objects. In contrast, infants who saw a solidity event end in a Violation outcome banged the objects more than they dropped them, whereas infants who saw a support event end in a Violation outcome dropped the objects more than they banged them. However, this interaction must be interpreted in light of the predicted significant interaction between object type, event type, and outcome type, $F(1,36)=4.95$, $P=0.032$, partial $\eta^2=0.12$. The kinds of exploratory actions infants produced depended on whether they had seen a solidity or support event, whether they had seen an Expected or Violation outcome, and whether they were engaging with the target object or the new distractor object.

3.2 General discussion of Experiment 2

Experiment 2 showed that infants who witnessed a surprising event preferentially explored the object that behaved surprisingly over an entirely novel object that did not. The double dissociation in infants' behavior – wherein infants who saw a solidity

violation tended to actively bang the target object, whereas infants who saw a support violation tended to drop it – shows that infants tailored their exploratory actions to the type of violation seen. Infants performed differential actions only following Violation events, and only on the objects that had committed the violation. Furthermore, the dissociation in infants' actions on just the target object reveals two senses in which infants' behaviors were highly directed: they focused on the entity that had violated expectations, and they were relevant to the nature of the observed violation. Thus, infants' behaviors are not merely reflexive responses to the novelty of surprising outcomes, but instead reflect deeper attempts to learn about aspects of the world that failed to accord with expectations.

In conjunction with Experiments Series 1, these experiments demonstrate that infants are motivated to learn about and seek explanations from entities that behaved surprisingly. The well-documented phenomenon of infants looking longer to surprising events may in fact reflect an underlying bias to seek information from entities that violate expectations. What is more, infants' specific exploratory behaviors suggest that perceptual factors alone cannot explain their performance (as some have claimed; e.g., Cohen & Marks, 2002). This information-seeking behavior is arguably more sophisticated than the surprise-induced enhancement of learning acquired in studies with non-human animals, in which animals learned better about a conditioned stimulus following surprising events (e.g., Pearce & Hall, 1980). Here, the infants learned genuinely new information, and went well beyond the perceptual input to test specific hypotheses about specific kinds of surprising events.

4. Question 3: Do children learn more effectively following violation events?

Experiment Series 1 and 2 suggest that infants can use core knowledge to shape passive learning in which they acquired new information through observation, and active learning in which they initiated their own exploration and explanation-seeking from objects that behaved surprisingly. An important question is whether this phenomenon is limited to preverbal infant learners, or whether it is a general feature of human learning that occurs throughout the lifespan and in diverse environments.

Previous research has shown that children are motivated to explore and explain evidence that is ambiguous or inconsistent with prior beliefs (Schulz & Bonawitz, 2007; Bonawitz et al., 2012; Legare et al., 2010; Legare, 2012; van Schijndel et al., 2015; Chandler & Lalonde, 1994) (see Section 1.5). But it remains an open question whether violations of core knowledge principles can guide learning of new information in young children.

I addressed this question by testing preschool-aged children outside of the controlled laboratory setting, here asking whether preschoolers also experience enhanced learning from surprising events in a more naturalistic learning environment, that of a children's science museum. Rather than probing whether children learned arbitrary object-sound associations (as in Experiment Series 1), I asked whether surprise would affect children's ability to learn novel words (that described either events that were novel but entirely possible, or similar events that were impossible in that they violated a principle of core object knowledge).

Children of this age are naturally engaged in learning new words, and can learn novel words in a single exposure (Carey & Bartlett, 1978). Nonetheless, children are variable in their vocabulary development (Fenson et al., 1994). The Intermodal Preferential Looking Paradigm has been instrumental in uncovering infants' and children's word comprehension (Golinkoff, Hirsh-Pasek, Cauley, & Gordon, 1987; Golinkoff, Ma, Song, & Hirsh-Pasek, 2013). Two images are presented side-by-side, and children hear accompanying linguistic information. Their comprehension is measured by whether they look to or point at the matching image. This method, as well as parental report, has shown that verbs in particular are more difficult to learn than nouns (e.g., Golinkoff, Jacquet, Hirsh-Pasek, & Nandakumar, 1996; Gentner, 1982; Bornstein et al., 2004), as verbs are ephemeral, relational, and their meaning often relies on the syntactic structure of a sentence (Golinkoff & Hirsh-Pasek, 2008 for review). Children often require multiple exposures and contrastive examples to learn novel verbs (e.g., Waxman, Lidz, Braun, & Lavin, 2009).

It is unknown whether witnessing surprising events would boost children's word learning as it does for infants' learning of hidden auditory properties. In Experiments 3.1-3.4, I asked whether children learned more effectively following surprising events. All children were taught novel words that described expected and violation events, and were probed on their learning of these words.

4.1 Experiment 3.1 Children's learning of novel verbs following expected and unexpected events

I tested 3- to 6-year old children's word learning in the dynamic setting of a busy science museum. All children saw two triads of events. The first two events in each triad were filler events that were novel but physically possible. Following each event, the novel action was labeled with a distinct novel verb. The last event in the triad, the critical event, was either expected or surprising on the basis of core knowledge of object behavior – it culminated in either an Expected or Violation outcome to spatiotemporal continuity (e.g., Wilcox et al., 1996). In this critical event, a toy was hidden under one of two cups, and was either revealed under the same cup after a spatial displacement (Expected outcome), or was magically revealed under the other cup (Violation outcome). The action in either of these events was labeled with a novel verb, and children were tested on whether they mapped the novel verb from the critical event to the correct object.

The critical event in the other triad culminated in either an Expected or Violation outcome to featural continuity (Wilcox, 1999). A green doll was dropped into a bag, and an orange doll was removed either from a bag that already contained another doll (Expected outcome), or from a bag that was previously shown to be empty (Violation outcome). Again, children were taught a novel verb for the action in the critical event and were probed on whether they successfully learned this novel verb.

All children saw one triad of events culminate in an Expected outcome, and one triad of events culminate in a Violation outcome. Unlike the between-subjects design in Experiment Series 1, this within-subjects design allowed me to ask whether within a given child, word learning was enhanced for surprising relative to expected events. Each

child had just a single opportunity to learn the novel verb, and a single test trial in which to demonstrate their knowledge.

Method

Participants. Thirty-eight children between 3 and 6 years old participated (range = 3 years, 1 month, 5 days – 6 years, 10 months, 6 days; mean = 4 years, 8 months, 3 days; 19 females). Four additional children were excluded due to refusing to play the game (1) or experimenter error (3). All children in Experiments 3.1 to 3.4 were visitors to the Maryland Science Center and were invited to participate by a second experimenter who was greeting families on the museum floor. Parents of all children provided written informed consent prior to children's participation.

Stimuli. Children sat in a small chair in front of a table with the experimenter sitting across from them.

Spatiotemporal Continuity block. A black stage (46 x 15 x 30 cm) constructed out of wood sat on the table. The stage had two small circular trap doors that the experimenter could activate with hidden knobs. When the hidden knobs were turned, the trap doors allowed objects that were placed on top of them to be flipped out of view underneath the stage surface, and objects hidden underneath the stage (that were attached magnetically to the trap door's surface) to be flipped up to become visible on the stage surface.

A green clay wheel with a cross-hatched texture (4 cm diameter, 2 cm high) served as the acted upon object throughout this triad of events. Three distinctive pairs of opaque cups were used to perform the target actions: a pair of tall, thin red cups (9 cm

diameter, 15.5 cm high) with vertical stripes made of red ribbon; a pair of shiny orange cups (11.5 cm diameter, 7 cm high) with beveled edges; and a pair of wide blue bell-shaped cups (14.5 cm diameter, 9 cm high) with a blue checkerboard pattern.

Featural Continuity block. A green felt doll (7 x 13.5 cm) served as the acted upon object throughout this triad of events, and three other felt dolls (red, orange, and brown) were used just in the critical Expected and Violation events. Three distinctive containers were used to perform the target actions: a woven yellow basket (12 x 9 x 14 cm) with a clear plastic container inside (6 x 7 x 6 cm); a translucent blue box (17 x 12 x 3 cm) that contained a Velcro sticker; and a red velvet bag (12 cm diameter, 18.5 cm long) with a wooden handle. The bag was designed to be used in professional magic tricks because it had a secret compartment. Its main compartment could be accessed through the top opening or through a zippered opening at the bottom, but it also contained a hidden compartment that could only be accessed when the experimenter surreptitiously moved a lever underneath the handle. Moving the lever changed which compartment was accessible, so that an object placed in the bag could appear to vanish, or an empty bag could appear to suddenly contain something (both violations of continuity).

Procedure. All children were tested in two test blocks. The first two events in each block were filler events that were always physically possible, but that were designed to be salient, novel, and to involve an action for which children did not have any existing verbal label. The last event in each test block, the critical event, was either physically possible (i.e., ended in an Expected outcome) or physically impossible (i.e., ended in a Violation outcome). Children were taught a novel verb after each of these events, and thus they had the opportunity to learn a total of six novel words over the course of the

experiment. They were tested on whether they learned the novel verb from the critical events. Half of the children saw the Spatiotemporal Continuity block culminate in a Violation outcome and the Featural Continuity block culminate in an Expected outcome, and the other half saw the reverse. Block order was counterbalanced across children.

Spatiotemporal Continuity Block

Filler Event 1. The experimenter said, “I’m going to put this toy right here,” and placed the green toy on the left side of the stage surface. She then held the two red cups out, one in each hand, so that children could see inside them. The left cup visibly contained a green cloth. The experimenter said, “See these? Do you see what’s in there? Watch this!” and lowered the cups facedown onto the stage, the left one covering the toy. She lifted the cups to reveal that the toy had been covered by the cloth, and then said, “Look what happened!” The experimenter pointed to the cups and said, “These *daxed* the toy!” She then cleared everything from the stage. The covering of a toy with a cloth was designed to be possible, but novel.

Filler Event 2. The experimenter placed the same green toy on the right side of the stage surface. She held the two orange cups, one in each hand, so that children could see inside of them. The right cup visibly contained colored confetti. The experimenter said, “See these? Do you see what’s in there? Watch this!” and lowered the cups facedown onto the stage, the right one covering the toy. She lifted the cups to reveal that the toy had been covered with the confetti and said, “Look what happened!” The experimenter then pointed to the cups and said, “These *fepped* the toy!” She then cleared everything from the stage. The covering of a toy with confetti was designed to be possible, but novel.

Event 3 (Critical Event). The experimenter placed the same green toy on the left side of the stage. She held the two blue cups out, one in each hand, so that children could see inside of them and could observe that both were empty. She said, “See these? Watch this!” and lowered the cups facedown onto the stage, the left one covering the toy.

In the Expected outcome, the experimenter held both cups and, without lifting them, swapped their locations (as in a shell game). Thus, the cup that contained the toy was now on the right. The experimenter momentarily removed her hands from the cups, then lifted the cups to reveal that the toy was now on the right side of the stage. This outcome was considered expected, because children had seen the cups swap locations (Figure 10). As with the two filler events that had just occurred, this event was designed to be possible but novel.

In the Violation outcome, the experimenter left the cups in their original resting locations and momentarily removed her hands from the cups. As she did this, she secretly turned the knobs behind the stage to activate the trap doors. This made the object under the cup in the original left-hand location flip out of view underneath the stage, and made the empty surface in the right-hand location flip upward so that a duplicate toy rested on the stage under the right cup. The experimenter then lifted the cups to reveal the toy on the right side of the stage, so that it appeared to have vanished from under the left cup and reappeared under the right cup (thus violating spatiotemporal continuity). Critically, the final outcomes of the Expected and Violation events were perceptually identical (the toy was revealed under the cup on the right), but expected in one case and surprising in the other. Immediately following either the Expected or Violation outcome, the

experimenter said, “Look what happened!” then pointed to the cups and said, “These *blicked* the toy!” She then cleared everything from the stage (Figure 10).

Test trial. Immediately following this third event, the experimenter brought out a tray holding one cup of each type (red, orange, blue), with spatial position counterbalanced across children. She always probed children’s learning of the verb that had been taught after the final, critical event by saying, “If I wanted to *blick* the toy again, which one should I use? Which one will *blick* the toy?” (Figure 10). Children were prompted to point to the object that could be used to *blick* the toy. If children did not respond immediately, the experimenter repeated the question (e.g., “Which one will *blick* the toy?”) until children answered.

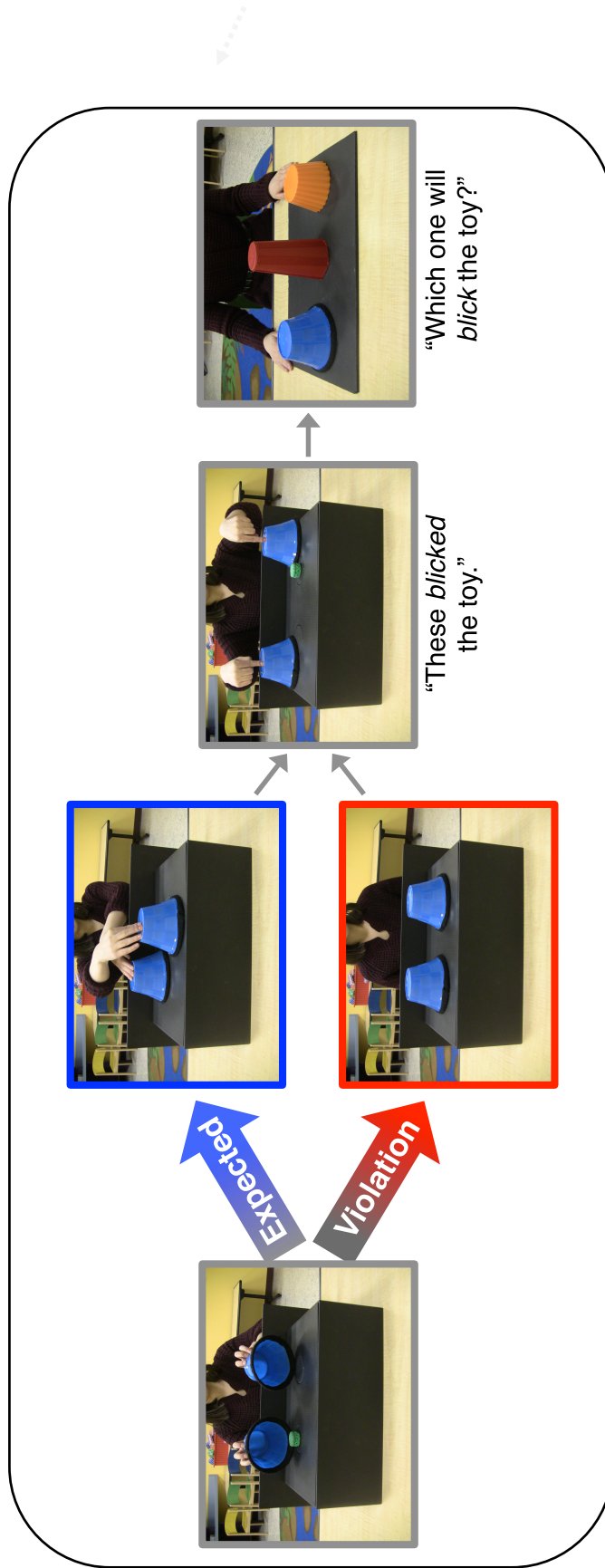


Figure 10. Event sequence for the critical Spatiotemporal Continuity event in Experiment 3.1. Children saw a toy hidden under the left cup. The experimenter then either swapped the cups in location and revealed the toy under the cup that was now on the right (Expected outcome), or left the cups in place yet revealed the toy under the cup on the right (Violation outcome). She then taught children a novel verb to describe the action. In the test trial, children were presented with the cup from the critical event and the cups from the filler events and were probed on the novel verb from the critical event.

Featural Continuity Block

Filler Event 1. The experimenter showed children the yellow basket with the transparent container inside. She held the doll above the basket and said, “Watch this, I’m going to put him inside!” She shook the basket as she squeezed the doll so that it fit into the transparent container within the basket. The experimenter then removed the transparent container to reveal the doll compressed inside and said, “Look what happened!” She wiggled the basket and said, “This *tizzed* him!” She cleared everything from the table. The squeezing of a toy into a tight container was designed to be possible, but novel.

Filler Event 2. The experimenter showed children the blue box with the Velcro sticker inside. She held the doll above the box and said, “Watch this, I’m going to put him inside!” She placed the doll in the box, closed the box and shook it, then removed the doll from the box to reveal that the Velcro sticker had stuck to the doll. She held up the doll and said, “Look what happened!” The experimenter wiggled the blue box and said, “This *zavved* him!” She cleared everything from the table. The doll getting stuck to a shirt was designed to be possible, but novel.

Event 3 (Critical Event). The experimenter brought out the red bag. In the Expected outcome, the experimenter first showed children that the bag was empty by unzipping it, sticking her arm through it, and looked through one side while children looked through the other. Once children agreed that the bag was empty, the experimenter zipped the bag closed. She then showed them the three dolls (red, orange, and brown) and placed them inside the bag, saying “Watch this, I’m going to put these inside!” She then said, “I’m going to take just these two out” as she removed the red and brown dolls,

showing them to children before placing them out of sight. She then said, “But there is still another one inside! Can you feel it?” and prompted children to feel the bulge in the bag where the remaining orange doll rested. She then held up the original green doll and told children that she was going to put that doll inside the bag. She dropped the doll in and shook the bag. Finally, the experimenter reached in and pulled the orange doll out. This outcome was considered expected, because children had previously seen the orange doll hidden in the bag and had never seen it removed (Figure 11).

For children who saw the Violation outcome, an orange doll was secretly pre-hidden in the bag’s secret compartment. The experimenter started by showing children three new felt dolls: one red, one orange, and one brown. She showed children as she placed them inside the bag, saying “Watch this, I’m going to put these inside!” She then prompted children to feel the bulge in the bag where the dolls were (this was done so as to match children’s experience with that in the Expected outcome). She said, “Now I’m going to take all of them out,” and removed all three dolls and showed them to children before placing them out of sight. The experimenter demonstrated that the bag was now completely empty, exactly as she did in the Expected outcome (by unzipping the bottom and prompting children to look through the apparently empty bag – note the orange doll was inside, but hidden in the secret compartment). She then held up the original green doll and told children that she was going to put it in the bag, dropped it inside and shook the bag. As she did this, she flipped the hidden lever on the bag’s handle so that the secret compartment containing the hidden orange doll became accessible. The experimenter reached into the bag and pulled the orange doll out, so that it appeared that the green doll had turned into the orange doll (a violation of featural continuity). As with the

Spatiotemporal Continuity event, the final outcome of the Expected and Violation events was identical: an orange doll was removed from the bag. Immediately following either the Expected or Violation outcome, the experimenter said, “Look what happened!” then wiggled the bag and said, “This *moxed* him!” (Figure 11).

Test trial. Immediately following this third critical event, the experimenter brought out a tray holding one container of each type (yellow basket, blue box, red bag). She always probed children’s learning of the verb that had been taught after the final, critical event by saying, “If I wanted to *mox* him again, which one should I use? Which one will *mox* him?” (Figure 11).

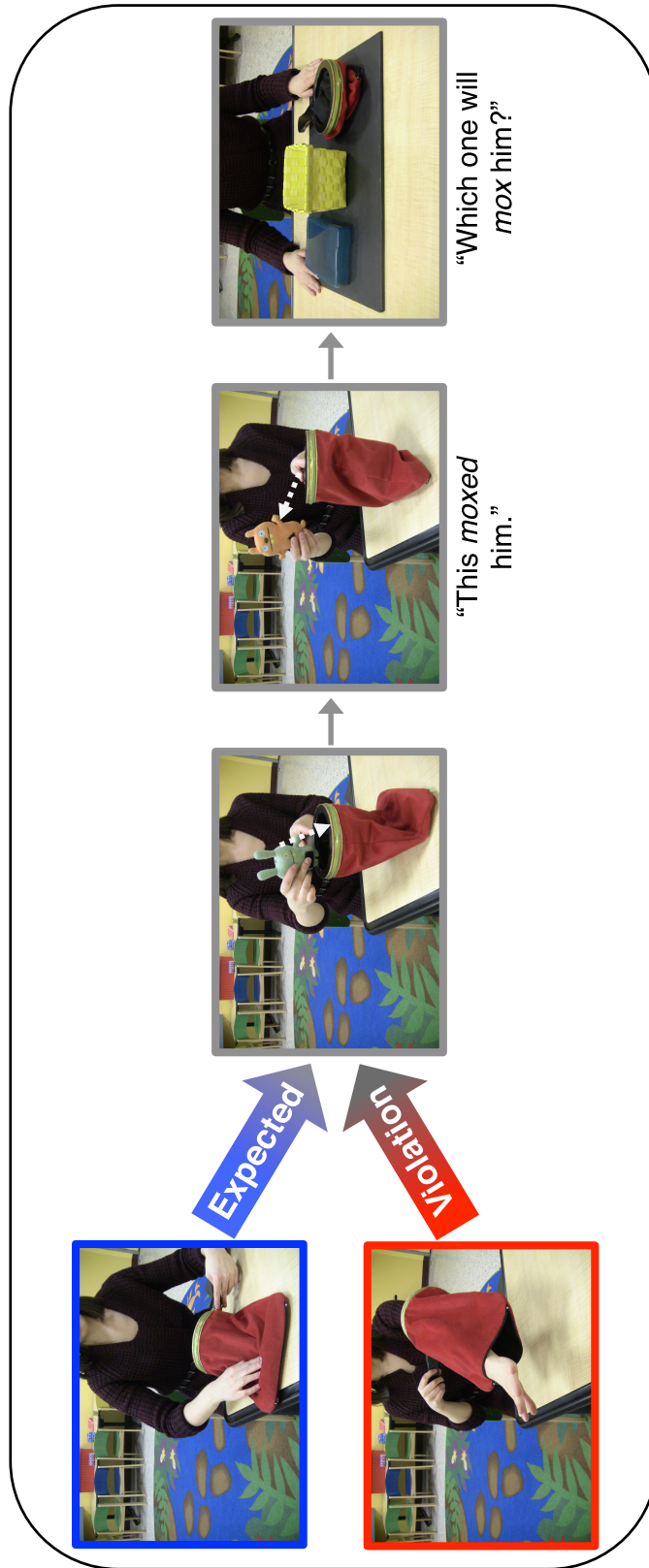


Figure 11. Event sequence for the critical Featural Continuity event in Experiment 3.1. Children either were shown a bag that already contained a doll inside, then saw a green doll placed into the bag and an orange doll removed (Expected outcome), or were shown an empty bag and then saw the green doll placed inside and an orange doll removed (Violation outcome). The experimenter then taught children a novel verb to describe the action. In the test trial, children were presented with the bag from the critical event and the containers from the filler events and were probed on the novel verb from the critical event.

Results

The goal of Experiment 3.1 was not to compare children's learning of the verb taught after the critical event to learning of the verbs taught after the filler events. Rather, the design of Experiment 3.1 allowed me to compare learning across children following two nearly identical versions of a single event: learning following an event that ended in an Expected outcome, versus learning following the same event that ended in a Violation outcome. The proportion of children's correct responses at Test was compared to chance (0.33, as there were three objects to choose from on each test trial) using a binomial test.

I found that children who had been taught a verb for an action that culminated in an Expected outcome chose at chance for both spatiotemporal continuity events (6 out of 17 children, 0.35, $P=0.51$) and featural continuity events (7 out of 21 children, 0.33, $P=0.57$). In contrast, children who had been taught the same verb for a nearly identical action that culminated in a Violation outcome exhibited robust learning; they chose the correct object at above chance levels following violations to spatiotemporal continuity (12 out of 21 children, 0.57, $P=0.02$) and featural continuity (14 out of 17 children, 0.82, $P<0.001$) (Figure 12).

I directly compared children's verb learning following surprising and expected events using a McNemar test (two-tailed, uncorrected). More children answered correctly following a Violation outcome and answered incorrectly following an Expected outcome than the reverse (14 vs. 1), $X^2(1)=11.27$, $P<0.001$. Thus, children's learning of novel verbs was enhanced following surprise.

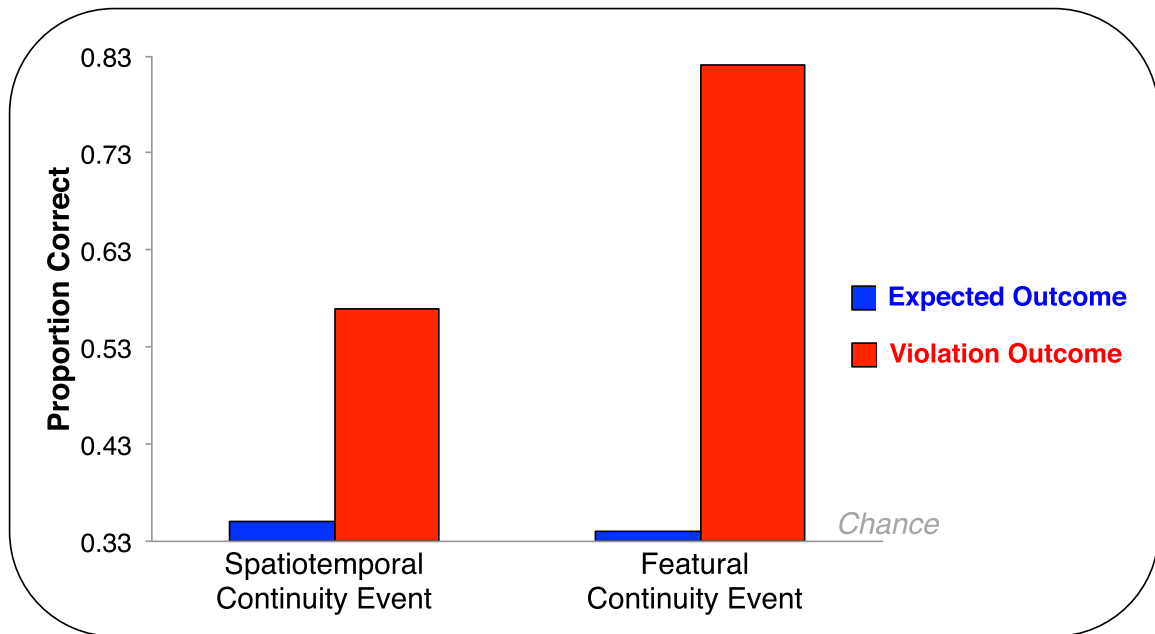


Figure 12. Results from Experiment 3.1. Bars represent proportion of children who selected the correct object when probed for the novel verb from the critical event (chance = 0.33).

4.2 Experiment 3.2 Children's learning of novel nouns following expected and unexpected events

Children in Experiment 3.1 demonstrated fast and robust learning for verbs that described surprising actions, whereas children failed to learn verbs that described perceptually similar actions that were physically possible (but also novel). Next I sought to replicate this finding for the learning of words from another grammatical category. In particular, I taught children nouns that described the acting objects in the events, rather than the actions themselves. Given that nouns are acquired earlier and easier to learn than verbs (e.g., Fenson et al., 1994; Bornstein et al., 2004; Gentner, 1982; Maguire, Hirsh-Pasek, & Golinkoff, 2006; Imai et al., 2008), this experiment allowed me to ask whether despite this benefit for noun learning, children still experienced enhanced learning following surprising events.

Method

Participants. Fifty-four children between 3 and 6 years old participated (range = 3 years, 7 days – 6 years, 10 months, 10 days; mean = 5 years, 24 days; 27 females).

Sixteen additional children were excluded for refusing to play the game (5), experimenter error (1), inattentiveness (6), parental/sibling interference (2), watching another child participate prior to testing (1), or missing birth date information (1).

Procedure. The procedure was identical to that of Experiment 3.1 with one exception. Instead of labeling each of the three events in each test block with novel verbs, the experimenter labeled the target objects with novel nouns. That is, instead of saying that the cups in the Spatiotemporal Continuity block had *daxed/fepped/blicked* the toy, she labeled the cups as *daxers/feppers/blickers*. For example, after the critical third event in the Spatiotemporal Continuity block, the experimenter pointed to the pair of blue cups (that had either been seen to move the toy from one position to the other by tracing a spatiotemporally continuous path, as in a shell game, or that had been seen to magically “teleport” the toy from one location to the other) and said, “These are *blickers*!” Similarly, instead of telling children that the containers in the Featural Continuity block had *tizzed/zavved/moxed* the doll, the experimenter labeled each container as a *tizzer/zavver/moxer* (e.g., “This is a *moxer*!”). In the test trial, she asked, “If I wanted to play with the *blicker/moxer* again, which one should I use? Which one is the *blicker/moxer*?”

Results

As in Experiment 3.1, I compared children’s learning following the critical Expected and Violation outcomes. I found that children who were taught the novel noun

label following an action that culminated in an Expected outcome chose at chance for both spatiotemporal continuity events (10 out of 27 children, 0.37, $P=0.39$) and featural continuity events (10 out of 27 children, 0.37, $P=0.39$). In contrast, children who had been taught the same novel noun following an nearly identical action that culminated in a Violation outcome exhibited robust learning; they chose the correct object at above chance levels following violations to spatiotemporal continuity (16 out of 27 children, 0.59, $P=0.004$) and featural continuity (14 out of 27 children, 0.52, $P=0.03$) (Figure 13). Again, more children answered correctly following a Violation outcome and incorrectly following an Expected outcome than the reverse (18 vs. 8), $X^2(1)=3.846$, $P=0.049$.

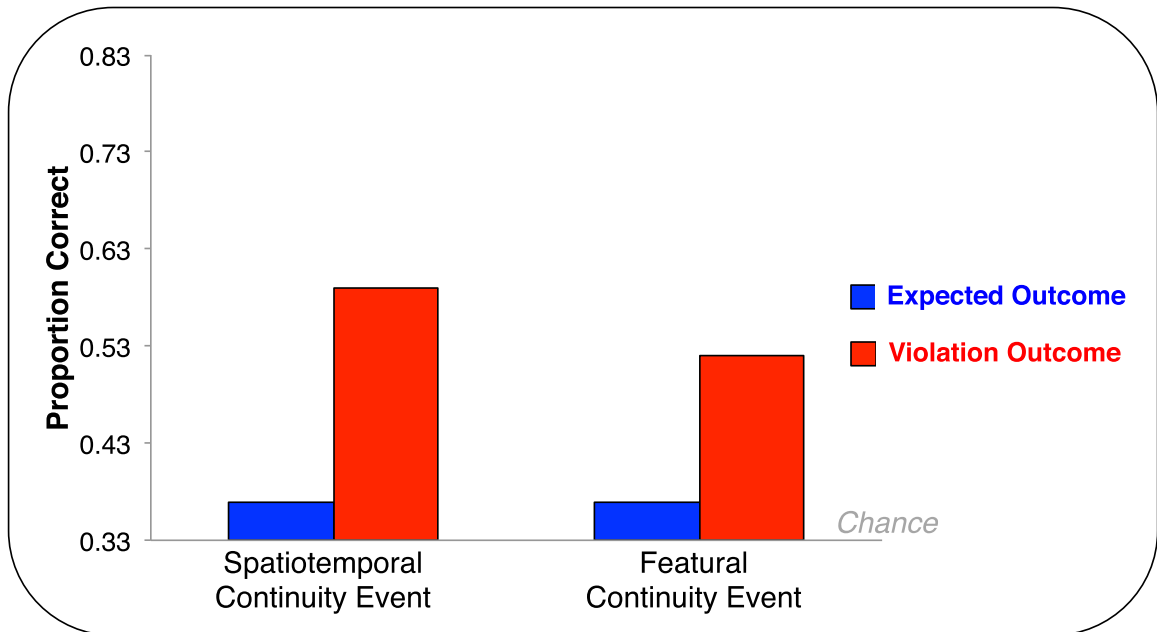


Figure 13. Results from Experiment 3.2. Bars represent proportion of children who selected the correct object when probed for the novel noun from the critical event (chance = 0.33).

4.3 Experiment 3.3 Ruling out perceptual preference for surprising objects

One alternative explanation of the results of Experiments 3.1 and 3.2 is that children selected the correct object at above chance levels following Violation events because they simply preferred that object over the distractor objects from the filler events. The results of Experiment 1.2 showed that 11-month-old infants successfully learned new information about an object that behaved surprisingly, and did not merely have a preference to look at that object – if the preschool-aged children in Experiments 3.1 and 3.2 also detected the violations of spatiotemporal and featural continuity (as the results of those experiments suggest they did), children might have pointed to objects that committed violations not because they learned novel verbs (e.g., which one could *blick* the toy) and novel nouns (e.g., which one is a *blicker*), but because they want to further explore objects that behaved in surprising ways. Experiment 3.3 was designed to test this possibility. Children saw the same series of events and learned novel verbs just as in Experiment 3.1. But this time, instead of probing children’s learning of the novel verb taught following the critical event, I probed their learning of a word taught after one of the filler events (which was always novel but physically possible). If children’s performance in Experiments 3.1 and 3.2 reflected attraction to surprising objects rather than actual learning, then here in Experiment 3.3 they should erroneously pick the object that had participated in a violation event.

Method

Participants. Thirty-four children between 3 and 6 years old participated (range = 3 years, 28 days – 6 years, 10 months, 21 days; mean = 5 years, 2 months, 5 days; 11

females). Seven additional children were excluded for refusal to play (2), experimenter error (3), watching another child participate prior to testing (1), or missing birth date information (1).

Procedure. The procedure was identical to that of the Experiment 3.1, with one exception. During the test trial, the experimenter asked children about the word that had been taught following the second filler event in each test block (which was always physically possible). In the Spatiotemporal Continuity block, this corresponded to the orange cups that had covered the toy with confetti. The experimenter said, “If I wanted to *fep* the toy again, which one should I use? Which one will *fep* the toy?” In the Featural Continuity block, this corresponded to the blue box in which the doll had become stuck to a Velcro sticker. The experimenter said, “If I wanted to *zav* him again, which one should I use? Which one will *zav* him?”

Results

If children were simply drawn to an object that had violated their expectations, they should again choose the third object from the critical Violation outcome in the test trial at above chance levels. However, I found that children who were asked for the object from the second filler event did not select the object from the third, critical event at above chance levels following either a Violation to spatiotemporal continuity (4 out 18 children, 0.22, $P=0.89$) or featural continuity (8 out of 16 children, 0.50, $P=0.12$). Likewise, children did not select this object following the Expected outcome to spatiotemporal continuity (5 out of 16 children, 0.31, $P=0.65$) or featural continuity (7 out of 18 children, 0.39, $P=0.38$) (Figure 14). Equal numbers of children chose this third object following a

Violation but not following an Expected outcome as the reverse (7 vs. 7), $\chi^2(1)=0$, $P=1.0$, suggesting that children's success in Experiments 3.1 and 3.2 reflected successful word learning rather than mere preference for objects that had violated expectations.

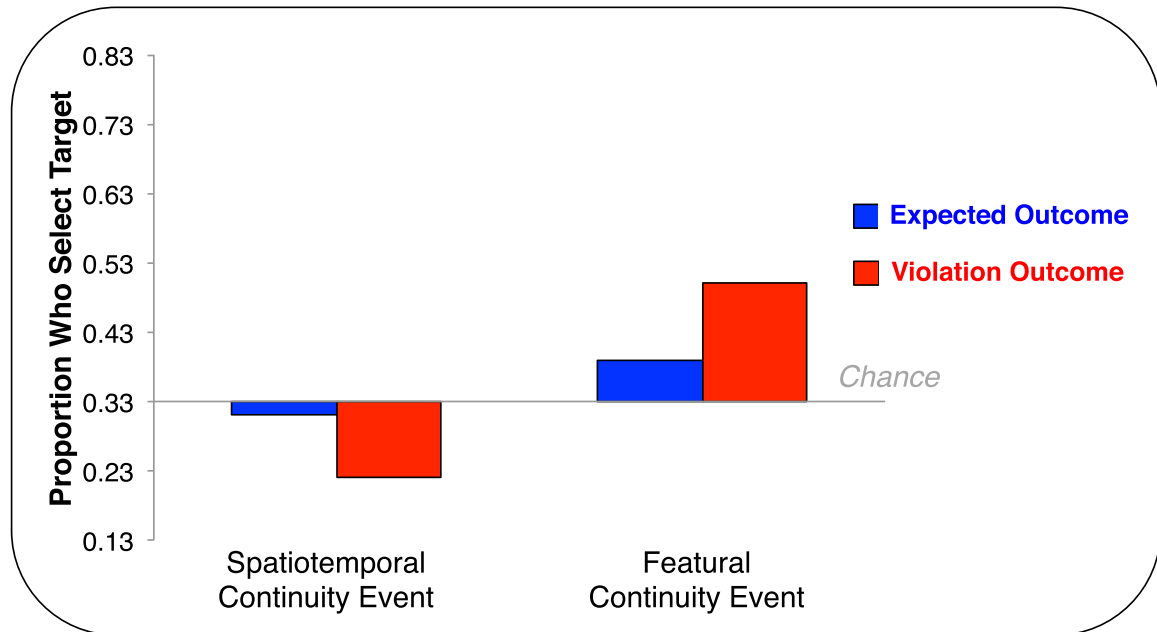


Figure 14. Results from Experiment 3.3. Bars represent proportion of children who selected the target object from the critical event when probed for a novel verb from a filler event (chance = 0.33).

4.4 Experiment 3.4 Children's learning about new objects following unexpected events

In Experiment 3.4 I explored whether witnessing surprising events enhances learning only about objects that participated in the event, or if surprise enhances learning more generally to objects present but not relevant to the surprise. Infants from Experiment 1.3 failed to learn about an entirely novel object that was presented following surprising events, indicating that their enhanced learning was restricted to entities that behaved surprisingly. In contrast, in the present study an “innocent bystander” object was present during each event, but did not participate in the event. I labeled these bystander

objects with novel nouns, and measured whether children learned words for the bystander objects present for Violation events more effectively than those present for Expected events. If surprise enhances learning for any entity that was present during a Violation event (perhaps due to increased attention or arousal), children should learn novel words for the bystander objects better following Violation events than Expected events. On the other hand, if surprise only enhances learning for objects that are relevant to the violation (as in Experiment 1.3 with infants), then children should fail to learn the novel labels for these bystander objects.

Method

Participants. Thirty-eight children between 3 and 6 years old participated (range = 3 years, 1 month, 27 days – 6 years, 7 months, 14 days; mean = 4 years, 9 months, 6 days; 14 females). Eleven additional children were excluded for refusal to play (2), experimenter error (3), inattentiveness (4), or missing birth date information (2).

Stimuli. The same stimuli were used as in Experiment 3.2. Three additional unique novel objects were used in the Spatiotemporal Continuity block (metal drain-like objects around 8 cm) (Figure 15A), and three additional unique novel objects were used in the Featural Continuity block (plastic, plug-like objects around 15 cm) (Figure 15B). These novel objects were chosen to be entirely novel to children, and also to be visually distinctive from one another but to share some perceptual properties (as did the cups in the Spatiotemporal Continuity block and the containers in the Featural Continuity block).

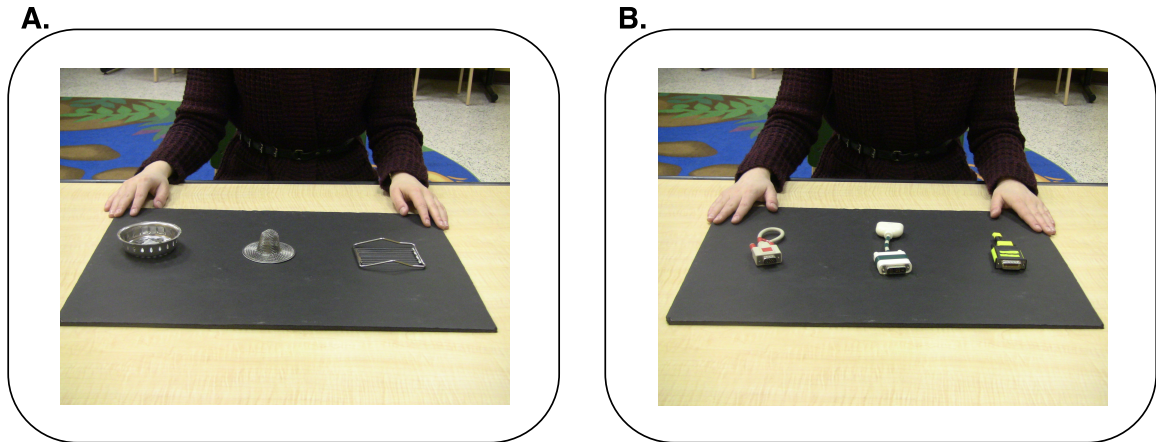


Figure 15. The novel “innocent bystander” objects from Experiment 3.4. A. Objects used in the Spatiotemporal Continuity block. B. Objects used in the Featural Continuity block.

Procedure. The procedure was identical to that of Experiment 3.2: in the Spatiotemporal Continuity block, children saw three distinct pairs of cups act on the green toy. In the Featural Continuity block, children saw three distinct pairs of containers act on the cloth doll. In addition, throughout each of the three events in each block, a unique novel object was present. In the Spatiotemporal Continuity block the novel object rested in the center of the stage, behind the other objects being shown to children. In the Featural Continuity block, the object rested on the table, next to the other objects being shown to children. The novel objects were always clearly visible to children but never participated in any of the events (e.g., they were “innocent bystanders”). After each event ended (e.g., the green toy was revealed under the right cup), the experimenter pointed to and labeled this bystander object (e.g., “This is a *blicker!*”) rather than labeling the object(s) that had participated in the event. At test, immediately following the last event in the block, children saw the three novel objects presented on a tray and were asked for the word that had been taught following the critical Expected or Violation outcome (i.e.,

“If I wanted to play with the *blicker/ moxer* again, which one should I use? Which one is the *blicker/ moxer*?”).

Results

Children did not learn the word for the bystander object following Expected outcomes to spatiotemporal continuity (9 out of 19 children, 0.47, $P=0.14$) or featural continuity (7 out of 19 children, 0.37, $P=0.44$). Similarly, children failed to learn the word for the bystander objects following Violations to spatiotemporal continuity (10 out of 19 children, 0.53, $P=0.06$) and featural continuity (8 out of 19 children, 0.42, $P=0.27$) (Figure 16). Most critically, children were equally likely to answer correctly when the bystander object had been labeled following a Violation outcome and incorrectly following an Expected outcome as the reverse (7 vs. 5), $\chi^2(1)=0.33$, $P=0.56$. Therefore, surprise appears to enhance learning in a targeted way: children’s learning was enhanced for objects and actions directly relevant to the surprising event, and not for irrelevant objects.

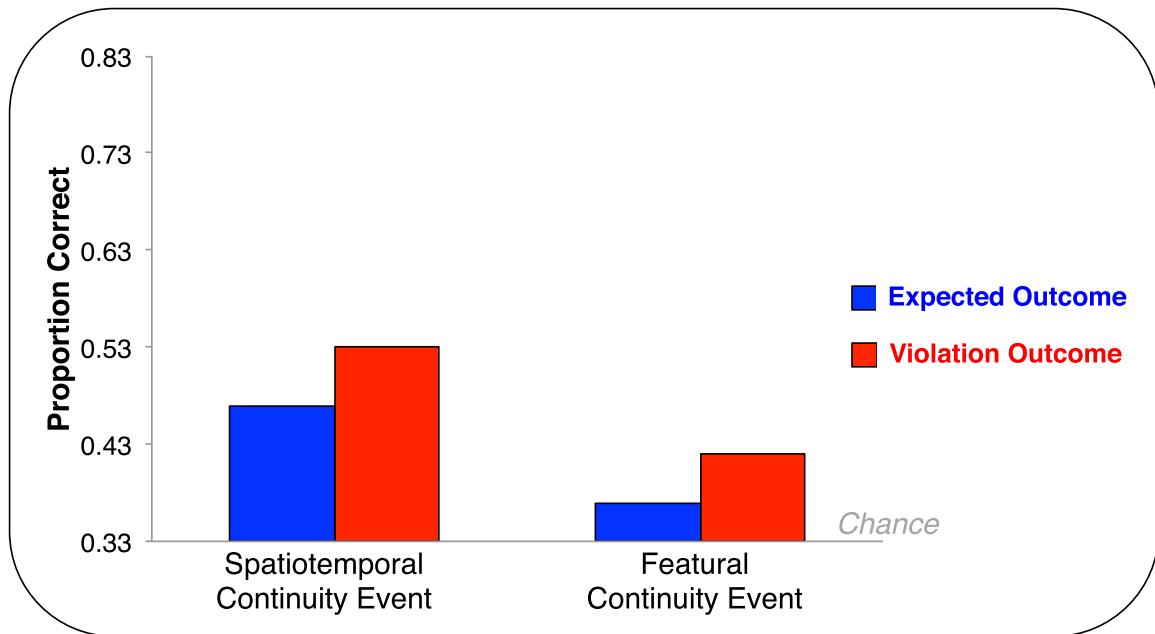


Figure 16. Results from Experiment 3.4. Bars represent proportion of children who selected the correct “innocent bystander” object when probed for the novel noun from the critical event (chance = 0.33).

4.5. General discussion of Experiments 3.1-3.4

Experiment 3.1 showed that children learned novel verbs more effectively following events that violated their expectations than following events that accorded with their expectations. Despite verb learning being notoriously difficult (e.g., Golinkoff & Hirsh-Pasek, 2008), children who witnessed surprising events learned these novel verbs from only a single exposure. Experiment 3.2 replicated these results with a different kind of novel word – nouns that labeled the objects themselves rather than the actions. Children still showed differential learning for nouns despite nouns being comparatively easier to learn (e.g., Imai et al., 2008).

Experiment 3.3 ruled out the alternative explanation that perhaps children selected the correct object following the Violation outcomes simply because they liked that object by virtue of it having had done something surprising. When children were probed with a

word that did not label the surprising action, children selected that object from the surprising events at chance levels.

Finally, Experiment 3.4 demonstrated that children showed no learning enhancement for objects that were not involved in the violation event, much like infants in Experiment 1.3. Interestingly, these “innocent bystander” objects were present for the entirety of the event, and could have conceivably been related to the surprising outcome. Nonetheless, children failed to learn the novel nouns that described these irrelevant objects following surprising events, indicating that they focused their learning on the particular entities that were relevant to the surprising actions. Together, Experiments 3.1-3.4 suggest that the surprise-induced enhancement of learning is perhaps a more general learning phenomenon that extends throughout the lifespan beyond infancy, outside of the controlled laboratory setting.

5. General Discussion

The last several decades of research have uncovered that infants have knowledge that is far more sophisticated than was once thought, and that at least some components of that knowledge are likely to be innate, in that they do not depend on specific experience (e.g., Spelke & Kinzler, 2007). The primary behavioral pattern used as evidence for this early “core” knowledge has been infants’ longer looking at surprising than expected events. The aim of my dissertation was to go beyond characterizing core knowledge, and to ask how this knowledge might empower further learning. In Experiment Series 1, I found that infants harnessed their core knowledge of objects to guide their learning. Specifically, I showed that 11-month-old infants learned new

information about an object better if that object defied their expectations about object behavior (i.e., by violating principles of solidity or spatiotemporal continuity).

Importantly, these differences in learning cannot be attributed to increased perceptual experience with objects in surprising outcomes. My experiments were designed such that infants did not have the opportunity to look longer at the outcomes of violation events, and yet they still learned better about objects that behaved surprisingly, indicating that longer looking and enhanced learning are independent consequences of experiencing surprising events.

In Experiment 2, I demonstrated that core knowledge not only enhances new learning, but it also scaffolds infants' self-guided exploratory behavior. Infants selectively explored an object that violated their expectations over an entirely novel object that had not, and explored that object in particular ways that suggested they were seeking an explanation for its strange behavior. Infants produced actions consistent with the view that they were testing hypotheses for specific kinds of surprising events: infants who saw an object pass through a wall appeared to test the object's solidity by banging it; in contrast, infants who saw an object float in mid-air appeared to test the object's means of support by dropping it. Thus, the kinds of surprising events infants observed modulated their exploratory behaviors.

Finally, in Experiment Series 3 I showed that this learning enhancement following surprising events is likely to be a general feature of human learning, at least during childhood. Three- to six-year-old children learned novel words more effectively for actions and objects involved in surprising events than expected events, and did so in a busy, naturalistic learning environment outside of the laboratory. Like infants, children

failed to learn novel information about objects that were irrelevant to the surprising event itself.

Together, these results suggest that surprise enhances learning across a range of ages (infants and preschoolers), environments (laboratory and museum), core principles of object behavior (solidity, spatiotemporal continuity, support, and featural continuity), learning contents (arbitrary object-sound mappings, explanations, and novel words), and dependent measures (looking, exploration, and pointing). Thus, surprising events appear to present a special opportunity to learn, not only in animals (e.g., Kamin, 1969) and human adults (e.g., den Ouden et al., 2009), but also in young learners who have more limited cognitive resources. Children and even untutored preverbal infants are sensitive to conflict between the predicted and the observed, and use this conflict to scaffold new learning.

In my experiments, I tested learning following violations of expectations drawn from core knowledge of object behavior – knowledge that is available from early in life, is universal across human cultures, and is present in other species. That violations of these foundational expectations – whose existence has been used to argue for the presence of rich innate knowledge in infants – lead to enhanced learning reveals a surprising harmony between early knowledge and early learning.

It is worth noting that it could have been the case that infants and children learned *more poorly* following these core knowledge violations than following expected events. For example, infants could have revised their understanding of the entities in the surprising events, such that the entity that behaved surprisingly was no longer considered a *bone fide* object after having violated a core principle of object-hood. Evidence for this

type of discarding of a previous object representation comes from previous findings – infants who see an object being broken in to pieces fail to track the broken pieces over occlusion (Cherries et al., 2008; Chiang & Wynn, 2000). Similarly, adults tracking multiple moving objects on a screen cease to effectively track them when the objects are seen to implode into and explode out of existence, or dissolve out of existence and then coalesce back into existence (e.g., Scholl & Pylyshyn, 1999; van Marle & Scholl, 2003).

Nonetheless, my results show that infants in this series of studies continued to represent an object following a violation of their expectations, such that they learned more effectively about it and explored it in remarkably sophisticated ways. Importantly, this phenomenon extends beyond infancy to older children, and is not constrained to the context of looking time tasks. The boost I observed in children’s learning of novel words occurred in a dynamic setting outside the laboratory, opening up the possibility that surprise may enhance learning across a variety of settings, including the classroom – a direction ripe for future inquiry.

By what mechanism might surprise enhance learning? One possibility is that seeing a surprising event causes observers to allocate more attention to the entity that behaved surprisingly. Models of animal learning posit such an effect: that attention to a cue that failed to accurately predict an outcome is increased, thereby enhancing learning about that surprising stimulus (e.g., Pearce & Hall, 2008; see section 1.4). Research has shown that attention indeed has a strong influence on memory in human observers. For example, adults instructed to remember a list of words showed reduced memory performance when their attention was divided with another task (e.g., Craik, Govoni,

Naveh-Benjamin, & Anderson, 1996; Mulligan, 1998; see also Baddeley, Lewis, Eldridge, & Thomson, 1984).

In addition to being implicated in memory, attention has also been shown to play a role in learning. For example, two groups of rats were exposed to identical auditory stimuli that varied in frequency and intensity. One group was reinforced to discriminate between frequencies, while the other group was reinforced to discriminate between intensities. Rats who attended to frequency learned to identify a frequency target but not an intensity target, and vice versa (Polley, Steinberg, & Merzenich, 2006; see Ahissar & Hochstein, 1993 for similar results with human adults). Thus, attention to the relevant feature improved learning of that particular feature. Attention not only enhances learning through reinforced conditioning, but also enhances incidental learning in humans (Turk-Browne, Jungé, & Scholl, 2005). In one task, adult observers watched a stream of serially presented red and green shapes. The order of the shapes within each color category were statistically structured in triplets, but the colors were interleaved throughout the stream. Observers were told to attend to one particular color and indicate when they saw an immediate repetition of a shape in the attended color. At test, the observers were shown triplets of shapes that maintained the statistical structure, and novel triplets of shapes that had appeared in the stream as parts of other triplets. Across a variety of conditions, observers incidentally learned the statistical structure of the shapes in the attended color and identified statistically intact triplets, but failed to do so for the unattended color. These results indicate that the allocation of attention influences learning (Turk-Browne et al., 2005).

It is possible, then, that infants' enhanced learning about (and perhaps even memory for) surprising objects is at least in part due to having allocated more attention to the target object than infants who saw the expected outcome. Although the experimental design ensured that infants' looking duration to the violation and expected outcomes did not differ, it is unknown to what aspect of the scene they attended. Eye-tracking data might be particularly useful as a means to analyze finer-grained patterns of infants' looking. For instance, infants who saw the expected outcome might have attended more to irrelevant aspects of the scene (e.g., the slope or color of the ramp). Conversely, infants who saw the violation outcome might have attended more to the object itself, leading to better learning about that object. Infants who saw the violation outcome also might have made more saccades between the object and critical items in the background (e.g., the relationship between the ball and the wall it appeared to pass through). This attention to the context of the violation also could have boosted infants' attention to and memory of such items, like the wall. Future experiments should investigate this possibility. Critically, however, this potential boost in attention must be highly localized to only those objects that participated the violation event, as infants and children failed to learn about objects that were completely irrelevant to the surprising event (see Experiments 1.3 and 3.4).

Another, related possibility for how surprise affected infants' and children's learning concerns the depth with which they processed the violation events. In particular, infants and children might have processed the outcomes of surprising events more deeply than expected events. It has previously been shown that adults who are prompted to more deeply process the words in a list (i.e., by answering questions about each word's semantic meaning) later recall more words from the list than adults prompted to process

the words more shallowly (i.e., by answering questions about their phonetic features) (Craik & Lockhart, 1972; Craik & Tulving, 1975). Children show a nearly identical pattern of performance (Murphy & Brown, 1973; Weiss, Robinson, & Hastie, 1977; Geis & Hall, 1977). Thus, it is possible that infants and children in my experiments processed the surprising object more deeply than those who saw the object behave as expected. Infants who saw an object behave surprisingly might have been impelled to think about the object more deeply – perhaps in the process, encoding features including the object’s hidden property (e.g., a sound it makes; see Experiment Series 1) or the object’s verbal label (see Experiment Series 3). Additionally, recent evidence suggests that mind-wandering selectively impairs deep processing in adults (Thomson, Smilek, & Besner, 2014). As described above, it is plausible that infants who saw the expected outcome distributed their attention more broadly and processed more unrelated details of the scene (e.g., the color of the ramp) rather than deeply encoding the properties of the target object. If this were true, infants who saw the expected outcome should remember more features of irrelevant items (e.g., the ramp), whereas infants who saw the surprising outcome should remember more features of highly relevant items (e.g., the ball) – a testable prediction.

It may also be informative to consider infants’ and children’s enhanced learning following surprising events from a Bayesian framework. On such a framework, infants and children are posited to have priors about, for example, object behavior (e.g., that objects are solid, cohesive entities); these priors might be set by evolution (i.e., they are innate) or by experience gained in the first weeks or months of life (i.e., they are acquired). They then observe evidence, which is weighed and then used to update priors

to posterior probabilities. A variety of kinds of information are relevant to this Bayesian process. For example, a learner can determine how expected the observation was given their prior hypotheses – on this view, surprise is best viewed not as a binary dimension (with events being either surprising or expected), but as a continuum (e.g., Téglás et al., 2011; Tenenbaum et al., 2011; Perfors et al., 2011; Schulz, 2012). According to Bayesian models of surprise (e.g., Courville et al., 2006; Baldi & Itti, 2010), infants might revise their posteriors to a greater degree upon receiving surprising evidence. This difference between the initial prior and the subsequent posterior signals a change and thus uncertainty in the prior, therefore leading to faster or better learning (which is compatible with the model by Pearce & Hall, 1980). This framework is not mutually exclusive with the aforementioned possibilities regarding increased attention and/or deeper processing of surprising events. In fact, it might be the difference between infants' priors and posteriors that induce a change in attention (Baldi & Itti, 2010; Itti & Baldi, 2009) or cause a change in the depth of processing that, in turn, enhance learning following core knowledge violations.

In the present series of studies I investigated the effects of violations of core knowledge of object behavior on learning in infants and children. Expectancy violations involving other types of knowledge, and other knowledge domains, are also likely to be important. For example, infants and children form new expectations by tracking experienced contingencies (e.g., Saffran et al., 1996), by receiving others' testimony (Jaswal, 2010), and by using abstract knowledge to form probabilistic predictions about events they have never before observed (e.g., Téglás et al., 2011). Some of these sophisticated behaviors have also been interpreted in terms of Bayesian inferences that

generate knowledge by weighing new evidence against prior beliefs (Tenenbaum, Griffiths, & Kemp, 2006; Schulz, 2012). These results open the door to asking how violations detected in different domains of prior knowledge, or using different kinds of new evidence, shape exploration and learning across the lifespan.

For example, one critical question is whether violations of events outside the core domain of objects would enhance learning as impossible core violations do. Even young infants can use probabilistic information to make inferences about whether outcomes are likely or unlikely to occur (e.g., Téglás et al., 2011; Téglás, Girotto, Gonzalez, & Bonatti, 2007; Xu & Garcia, 2008; Xu & Denison, 2009). Infants can also track visual and auditory statistical patterns and are sensitive to the degree to which those patterns are surprising. They prefer attending to statistical patterns that are neither too predictable nor too complex (the “Goldilocks effect”) (Kidd, Piantadosi, & Aslin, 2012; Kidd, Piantadosi, & Aslin, 2014). Counterintuitively, although I showed infants and children events that were designed to appear physically impossible (e.g., a ball passing through a wall), these events might still fall into the category of being only moderately surprising. More extreme violations, like a ball passing through the wall, splitting into dozens of other objects, changing identity, *then* disappearing might be far too unpredictable to attend to and learn about, because the outcome of this event is not even interpretable within the context in which the event was initially parsed.

Future experiments can explore what kinds of events might be optimally surprising to support subsequent learning. In ongoing studies I am presenting children with events in which an object is randomly drawn from a distribution. The probability of that object’s retrieval at random varies, such that some events are probable (e.g., 50%

likelihood), some events are impossible (e.g., 0% likelihood, as in the experiments in this dissertation), and critically, others are merely improbable (e.g., 5% likelihood). The question is whether children will learn more effectively following the improbable than the probable event, and if so, if they would learn as effectively from the improbable as the impossible event. If they do, this would suggest that violations that are surprising due to being unlikely enhance learning, much as impossible core knowledge violations do. If there is a difference in learning following improbable and impossible outcomes, there might indeed be evidence for an optimal amount of surprise to enhance learning, as the Goldilocks effect (Kidd et al., 2012; 2014) might suggest.

In summary, my experiments reveal that when young learners see an object defy their expectations, they learn about that object better, explore that object more, and test relevant hypotheses for that object's behavior. Seen through this lens, the decades of findings that infants look longer at surprising events suggest not only that infants are equipped with core knowledge about fundamental aspects of the world, but that, from early in the lifespan through childhood, this knowledge is harnessed to empower new learning. Thus core knowledge is not an alternative to learning, but instead a key ingredient in driving learning forward.

6. References

- Aguiar, A. & Baillargeon, R. (2002). Developments in young infants' reasoning about occluded objects. *Cognitive Psychology*, 45, 267-336.
- Ahissar, M. & Hochstein, S. (1993). Attentional control of early perceptual learning. *Proceedings of the National Academy of Sciences*, 90, 5718-5722.
- Aslin, R. N. (2007). What's in a look? *Developmental Science*, 10, 48-53.
- Baddeley, A., Lewis, V., Eldridge, M., & Thomson, N. (1984). Attention and retrieval from long-term memory. *Journal of Experimental Psychology: General*, 113, 518-540.
- Baillargeon, R. (1986). Representing the existence and the location of hidden objects: Object permanence in 6- and 8-month-old infants. *Cognition*, 23, 21-41.
- Baillargeon, R. (1987a). Object permanence in 3.5- and 4.5-month-old infants. *Developmental Psychology*, 23, 655-664.
- Baillargeon, R. (1987b). Young infants' reasoning about the physical and spatial properties of a hidden object. *Cognitive Development*, 2, 179-200.
- Baillargeon, R. (1991). Reasoning about the height and location of a hidden object in 4.5- and 6.5-month-old infants. *Cognition*, 38, 13-42.
- Baillargeon, R. (1999). Young infants' expectations about hidden objects: A reply to three challenges. *Developmental Science*, 2, 115-132.
- Baillargeon, R. & DeVos, J. (1991). Object permanence in young infants: Further evidence. *Child Development*, 62, 1227-1246.
- Baillargeon, R. & Graber, M. (1987). Where's the rabbit? 5.5-month-old infants'

- representation of the height of a hidden object. *Cognitive Development*, 2, 375-392.
- Baillargeon, R., Needham, A., & DeVos, J. (1992). The development of young infants' intuitions about support. *Early Development and Parenting*, 1, 69-78.
- Baillargeon, R., Spelke, E. S., & Wasserman, S. (1985). Object permanence in five-month-old infants. *Cognition*, 20, 191-208.
- Baldi, P. & Itti, I. (2010). Of bits and wows: A Bayesian theory of surprise with applications to attention. *Neural Networks*, 23, 649-666.
- Berkeley, G. (1732/1910). *A new theory of vision and other select philosophical writings*. New York: Dutton.
- Berger, A., Tzur, G., & Posner, M. I. (2006). Infant brains detect arithmetic errors. *Proceedings of the National Academy of Sciences*, 103, 12649-1653.
- Bonawitz, E. B., van Schijndel, T.J., Friel, D., & Schulz, L. (2012). Balancing theories and evidence in children's exploration, explanations, and learning. *Cognitive Psychology*, 64, 215-234.
- Bornstein, M. H., Cote, L. R., Maital, S., Painter, K., Park, S. Y., Pascual, L., Pecheux, M. G., Ruel, J., Venuti, P., & Vyt. A. (2004). Cross-linguistic analysis of vocabulary in young children: Spanish, Dutch, French, Hebrew, Italian, Korean, and American English. *Child Development*, 75, 1115-1139.
- Brown, J. W. & Braver, T. S. (2005). Learned predictions of error likelihood in the anterior cingulate cortex. *Science*, 307, 1118-1121.
- Bulf, H., Johnson, S. P., & Valenza, E. (2011). Visual statistical learning in the newborn infant. *Cognition*, 121, 127-132.

- Camras, L. A., Meng, Z., Ujiie, T., Dharamsi, S., Miyake, K., Oster, H., Wang, L., Cruz, J., Murdoch, A., & Campos, J. (2002). Observing emotion in infants: Facial expression, body behavior, and rater judgments of responses to an expectancy-violating event. *Emotion*, 2, 179-193.
- Carey, S. (2009). *The Origin of Concepts*. New York: Oxford University Press.
- Carey, S. & Bartlett, E. (1978). Acquiring a single new word. *Proceedings of the Stanford Child Language Conference*, 15, 17-29.
- Carter, C. S., Braver, T. S., Barch, D. M., Botvinick, M. M., Noll, D., & Cohen, J. D. (1998). Anterior cingulate cortex, error detection, and the online monitoring of performance. *Science*, 280, 747-749.
- Chandler, M. J. & Lalonde, C. E. (1994). Surprising, miraculous, and magical turns of events. *British Journal of Developmental Psychology*, 12, 83-95.
- Cherries, E. W., Mitroff, S. R., Wynn, K., & Scholl, B. J. (2008). Cohesion as a principle of object persistence in infancy. *Developmental Science*, 11, 427-432.
- Chiang, W. C., & Wynn, K. (2000). Infants' representation and tracking of multiple objects. *Cognition*, 77, 169-195.
- Chiandetti, C. & Vallortigara, G. (2010). Experience and geometry: Controlled-rearing studies with chicks. *Animal Cognition*, 13, 463-470.
- Chomsky, N. (1980a). On cognitive structures and their development: A reply to Piaget. In M. Piatelli-Palmarini (Ed.), *Language and learning: The debate between Jean Piaget and Noam Chomsky* (pp. 393-396). London: Routledge and Kegan Paul.
- Chomsky, N. (1980b). *Rules and representation*. New York: Columbia University Press.

- Cohen, L. B., & Marks, K. S. (2002). How infants process addition and subtraction events. *Developmental Science*, 5(2), 186-201.
- Colombo, J. (2001). The development of visual attention in infancy. *Annual Review of Psychology*, 52, 337-367.
- Courville, A. C., Daw, N. D., & Touretzky, D. S. (2006). Bayesian theories of conditioning in a changing world. *Trends in Cognitive Sciences*, 10, 294-300.
- Craik, F. I. M., Govoni, R., Naveh-Benjamin, M., & Anderson, N. D. (1996). The effects of divided attention on encoding and retrieval processes in human memory. *Journal of Experimental Psychology: General*, 125, 159-180.
- Craik, F. I. M. & Lockhart, R. S. (1972). Levels of processing: A framework for memory research. *Journal of Verbal Learning and Verbal Behavior*, 11, 671-684.
- Craik, F. I. M. & Tulving, E. (1975). Depth of processing and the retention of words in episodic memory. *Journal of Experimental Psychology: General*, 104, 268-294.
- Csibra, G. & Gergely, G. (2009). Natural pedagogy. *Trends in Cognitive Science*, 13, 148-153.
- DeCasper, A. J. & Fifer, W. P. (1980). Of human bonding: Newborns prefer their mothers' voices. *Science*, 208, 1174-1176.
- Dehaene, S., Izard, V., Pica, P., & Spelke, E. S. (2006). Core knowledge of geometry in an Amazonian indigene group. *Science*, 311, 381-384.
- den Ouden, H. E. M., Friston, K. J., Daw, N. D., McIntosh, A. R., & Stephan, K. E. (2009). A dual role for prediction error in associative learning. *Cerebral Cortex*, 19, 1175-1185.
- Descartes, R. (1637/1971). The dioptrics. In E. Anscombe & P. T. Geach (Eds.),

- Philosophical writings: Descartes* (pp. 239-256). Indianapolis, IN: Bobbs-Merril.
- Dickinson, A., Hall, G., & Mackintosh, N. J. (1976). Surprise and the attenuation of blocking. *Journal of Experimental Psychology: Animal Behavior Processes*, 2, 313-322.
- Elman, J. L., Bates, E., & Johnson, M. H. (1996). *Rethinking innateness: A connectionist perspective on development* (pp. 147-171). Cambridge, Massachusetts: The MIT Press.
- Everett, D. L. (2005). Cultural constraints on grammar and cognition in Pirahã: Another look at the design features of human language. *Current Anthropology*, 46, 621-646.
- Fantz, R. L. (1963). Pattern vision in newborn infants. *Science*, 19, 296-297.
- Fantz, R. L. (1964). Visual Experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science*, 146, 668-670.
- Feigenson, L. & Carey, S. (2003). Tracking individuals via object-files: Evidence from infants' manual search. *Developmental Science*, 6, 568-584.
- Feigenson, L., Carey, S., & Hauser, M. (2002). The representations underlying infants' choice of more: Object-files versus analog magnitudes. *Psychological Science*, 13, 150-156.
- Feigenson, L., Dehaene, S., & Spelke, E. S. (2004). Core systems of number. *Trends in Cognitive Sciences*, 8, 307-314.
- Fenson, L., Dale, P., Reznick, J., Bates, E., Thal, D., & Pethick, S. (1994). Variability in early communicative development. *Monographs of the Society for Research in Child Development*, 59, 1-185.

- Fletcher, P. C., Anderson, J. M., Shanks, D. R., Honey, R., Carpenter, R. A., Donovan, T., Papadakis, N., & Bullmore, E. T. (2001). Responses of human frontal cortex to surprising events are predicted by formal associative learning theory. *Nature Neuroscience*, 4, 1043-1048.
- Flombaum, J. I. & Santos, L. R. (2005). Rhesus monkeys attribute perceptions to others. *Current Biology*, 15, 447-452.
- Fodor, J. (1998). *Concepts: Where Cognitive Science Went Wrong*. New York: Oxford University Press.
- Gallistel, C. R. (1989). Animal cognition: The representation of space, time, and number. *Annual Review of Psychology*, 40, 155-189.
- Geis, M. F. & Hall, D. M. (1976). Encoding and incidental memory in children. *Journal of Experimental Child Psychology*, 22, 58-66.
- Gentner, D. (1982). Why nouns are learned before verbs: Linguistic relativity versus natural partitioning. In S. Kuczaj (Ed.), *Language development: language, cognition, and culture* (pp. 301-334). Hillsdale, NJ: Erlbaum.
- Golinkoff, R. M. & Hirsh-Pasek, K. (2008). How toddlers begin to learn verbs. *Trends in Cognitive Sciences*, 12, 397-403.
- Golinkoff, R. M., Hirsh-Pasek, K., Cauley, K. M., & Gordon, L. (1987). The eyes have it: Lexical and syntactic comprehension in a new paradigm. *Journal of Child Language*, 14, 23-45.
- Golinkoff, R. M., Jacquet, R., Hirsh-Pasek, K., & Nandakumar, R. (1996). Lexical principles may underlie the learning of verbs. *Child Development*, 67, 3101-3119.
- Golinkoff, R. M., Ma, W., Song, L., & Hirsh-Pasek, K. (2013). Twenty-five years using

- the intermodal preferential looking paradigm to study language acquisition: What have we learned? *Perspectives on Psychological Science*, 8, 316-339.
- Gordon, P. (2004). Numerical cognition without words: Evidence from Amazonia. *Science*, 306, 496-499.
- Gredebäck, G. & Melinder, A. (2010). Infants' understanding of everyday social interactions: A dual process account. *Cognition*, 114, 197-206.
- Gweon, H., & Schulz, L. E., (2011). 16-month-olds rationally infer causes of failed actions. *Science*, 332, 1524.
- Haith, M. M. (1998). Who put the cog in infant cognition? Is rich interpretation too costly? *Infant Behavior and Development*, 21, 167-179.
- Hare, T. A., O'Doherty, J., Camerer, C. F., Schultz, W., & Rangel, A. (2008). Dissociating the role of the orbitofrontal cortex and the striatum in the computation of goal values and prediction errors. *Journal of Neuroscience*, 28, 5623-5630.
- Hauser, M. D. & Carey, S. (2003). Spontaneous representations of small numbers of objects by rhesus macaques: Examinations of content and format. *Cognitive Psychology*, 47, 367-401.
- Hayden, B. Y., Heilbronner, S. R., Pearson, J. M., & Platt, M. L. (2011). Surprise signals in anterior cingulate cortex: Neuronal encoding of unsigned reward predictions errors driving adjustment in behavior. *The Journal of Neuroscience*, 31, 4178-4187.
- Helmholtz, H. von (1867/1962). *Treatise on physiological optics* (J. P. C. Southall, Trans.). New York: Dover.

- Hermer, L. & Spelke, E. S. (1996). Modularity and development: The case of spatial reorientation. *Cognition*, 61, 195-232.
- Hollerman, J. R. & Schultz, W. (1998). Dopamine neurons report an error in the temporal prediction of reward during learning. *Nature Neuroscience*, 1, 304-309.
- Huntley-Fenner, G., Carey, S., & Solimando, A. (2002). Objects are individuals but stuff doesn't count: Perceived rigidity and cohesiveness influence infants' representations of small groups of discrete entities. *Cognition*, 85, 203-221.
- Imai, M., Li, L., Haryu, E., Okada, H., Hirsh-Pasek, K., Golinkoff, R. M., & Shigematsu, J. (2008). Novel noun and verb learning in Chinese-, English-, and Japanese-speaking children. *Child Development*, 79, 979-1000.
- Itti, L. & Baldi, P. (2009). Bayesian surprise attracts human attention. *Vision Research*, 49, 1295-1306.
- Izard, V., Sann, C., Spelke, E. S., & Streri, A. (2009). Newborn infants perceive abstract numbers. *Proceedings of the National Academy of Sciences*, 106, 10382-10385.
- Jackson, I., & Sirois, S. (2009). Infant cognition: Going full factorial with pupil dilation. *Developmental Science*, 12, 670-679.
- James, W. (1890/1981). *The principles of psychology*. Cambridge, MA: Harvard University Press.
- Jaswal, V. K. (2010). Believing what you're told: Young children's trust in unexpected testimony about the physical world. *Cognitive Psychology*, 61, 248-272.
- Kamin, L. J. (1969). Predictability, surprise, attention, and conditioning. In B. A. Campbell & R. M. Church (Eds.), *Punishment and aversive behavior* (pp. 279-296). New York: Appleton-Century-Crofts.

- Kellman, P. J. & Spelke, E. S. (1983). Perception of partly occluded objects in infancy. *Cognitive Psychology*, 15, 483-524.
- Kidd, C., Piantadosi, S. P., & Aslin, R. N. (2012). The Goldilocks Effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PLoS ONE*, 7, 1-8.
- Kidd, C., Piantadosi, S. P., & Aslin, R. N. (2014). The Goldilocks effect in infant auditory cognition. *Child Development*, 85, 1795-1804.
- Kirkham, N. Z., Slemmer, J. A., & Johnson, S. P. (2002). Visual statistical learning in infancy: Evidence for a domain general learning mechanism. *Cognition*, 83, B35-B42.
- Kisilevsky, B., Hains, S. M. J., Lee, K., Xie, X., Huang, H., Ye, H. H., Zhang, K., Wang, Z. (2003). Effects of experience on fetal voice recognition. *Psychological Science*, 14, 220-224.
- Kuhl, P. K. & Meltzoff, A. N. (1984). The intermodal representation of speech in infants. *Infant Behavior and Development*, 7, 361-381.
- Kuhlmeier, V., Bloom, P., & Wynn, K. (2004). Infants do not see humans as material objects. *Cognition*, 94, 95-103.
- Kuhlmeier, V., Wynn, K., & Bloom, P. (2003). Attribution of dispositional states by 12-month-old infants. *Psychological Science*, 14, 402-408.
- Kundey, S. M., De Los Reyes, A., Taglang, C., Baruch, A., & German, R. (2010). Domesticated dogs' (*Canis familiaris*) use of the solidity principle. *Animal Cognition*, 13, 497-505.
- Lakusta, L., Dessalegn, B., & Landau, B. (2010). Impaired geometric reorientation

- caused by genetic defect. *Proceedings of the National Academy of Sciences*, 107, 2813-2817.
- Legare, C. H. (2012). Exploration explanation: Explaining inconsistent evidence informs exploratory, hypothesis-testing behavior in young children. *Child Development*, 83, 173-185.
- Legare, C. H., Gelman, S. A., & Wellman, H. M. (2010). Inconsistency with prior knowledge triggers children's causal explanatory reasoning. *Child Development*, 81, 929-944.
- Leslie, A. M. & Keeble, S. (1987). Do six-month-old infants perceive causality? *Cognition*, 25, 265-288.
- Locke, J. (1690/1975). *An essay concerning human understanding*. Oxford, UK: Oxford University Press.
- Luo, R., Baillargeon, R., Brueckner, L., & Munakata, Y. (2003). Reasoning about a hidden object after a delay: Evidence from robust representations in 5-month-old infants. *Cognition*, 88, B23-B32.
- Maguire, M., Hirsh-Pasek, K., & Golinkoff, R. M. (2006). A unified theory of word learning: Putting verb acquisition in context. In K. Hirsh-Pasek & R. M. Golinkoff (Eds.), *Action Meets Word: How Children Learn Verbs* (pp. 364-391). New York: Oxford University Press.
- Mash, C., Clifton, R. K., & Berthier, N. E. (2003). Visual access and attention in two-year-olds' event reasoning and object search. *Infancy*, 4, 371-388.
- McClure, S. M., Berns, G. S., Montague, P. R. (2003). Temporal prediction errors in a

- passive learning task activate human striatum. *Neuron*, 38, 339-346.
- McCrink, K. & Wynn, K. (2004). Large-number addition and subtraction by 9-month-old infants. *Psychological Science*, 15, 776-781.
- Meltzoff, A. N. (1995). Understanding the intentions of others: Re-enactment of intended acts by 18-month-old children. *Developmental Psychology*, 31, 838-850.
- Moon C., Cooper, R. P., & Fifer, W. P. (1993). Two-day-olds prefer their native language. *Infant Behavior and Development*, 16, 495-500.
- Moon, C., Lagercrantz, H., Kuhl, P. K. (2013). Language experience *in utero* affects vowel perception after birth: A two-country study. *Acta Paediatrica*, 102, 156-160.
- Morrongiello, B. A., Fenwick, K. D., & Chance, G. (1998). Crossmodal learning in newborn infants: Inferences about properties of auditory-visual events. *Infant Behavior & Development*, 21, 543-554.
- Mulligan, N. W. (1998). The role of attention during encoding in implicit and explicit memory. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, 24, 27-47.
- Murphy, M. D. & Brown, A. L. (1975). Incidental learning in preschool children as a function of level of cognitive analysis. *Journal of Experimental Child Psychology*, 19, 509-523.
- Needham, A. & Baillargeon, R. (1993). Intuitions about support in 4.5-month-old infants. *Cognition*, 47, 121-148.
- Newcombe, N. S., Sluzenski, J., & Huttenlocher, J. (2005). Pre-existing knowledge

- versus on-line learning: What do infants really know about spatial location? *Psychological Science*, 16, 222-227.
- O'Doherty, J., Dayan, P., Schultz, J., Deichmann, R., Friston, K., & Dolan, R. J. (2004). Dissociable roles of ventral and dorsal striatum in instrumental conditioning. *Science*, 304, 452-454.
- Onishi, K. H., & Baillargeon, R. (2005). Do 15-month-old infants understand false beliefs? *Science*, 8, 255-258.
- Parris, B. A., Kuhn, G., Mizon, G. A., Benattayallah, A. & Hodgson, T. L. (2009). Imaging the impossible: an fMRI study of impossible causal relationships in magic tricks. *Neuroimage*, 45, 1033-1039.
- Partanen, E., Kujala, T., Näätänen, R., Liitola, A., Sambeth, A., & Huotilainen, M. (2013). Learning-induced neural plasticity of speech processing before birth. *Proceedings of the National Academy of Science*, 110, 15145-15150.
- Pearce, J.M., & Hall, G. (1980). A model for Pavlovian learning: Variations in the effectiveness of conditioned but not of unconditioned stimuli. *Psychological Review*, 87, 532-552.
- Perfors, A., Tenenbaum, J. B., Griffith, T. L., & Xu, F. (2011). A tutorial introduction to Bayesian models of cognitive development. *Cognition*, 120, 302-321.
- Perone, S., & Oakes, L. M. (2006). It clicks when it is rolled and it squeaks when it is squeezed: What 10-month-old infants learn about object functions. *Child Development*, 77, 1608-1622.
- Piaget, J. (1954). *The construction of reality in the child*. New York: Basic Books.
- Pinker, S. (1994). *The language instinct*. New York: William Morrow and Company, Inc.

- Plato. (380 B.C.E/1892). *The dialogues of Plato*. (B. Jowett, Trans and Ed.). Thoemess Press.
- Polley, D.B., Steinberg, E. E., & Merzenich, M. M. (2006). Perceptual learning directs auditory cortical map reorganization through top-down influences. *Journal of Neuroscience*, 26, 4970-4982.
- Quine, W. V. O. (1960). *Word and object*. Cambridge: MA: MIT Press
- Regolin, L & Vallortigara, G. Perception of partly occluded objects by young chicks. *Perception & Psychophysics*, 57, 971-976.
- Rescorla, R. A. & Wagner, A. R. (1972). A theory of Pavlovian conditioning: Variations in the effectiveness of reinforcement and nonreinforcement. In A.H. Black and W.F. Prokasy (Eds.), *Classical conditioning II: Current research and theory* (pp. 64-99). New York: Appleton-Century-Crofts.
- Richardson, D. C., & Kirkhan, N. Z. (2004). Multimodal events and moving locations: Eye movements of adults and 6-month-olds reveal dynamic spatial indexing. *Journal of Experimental Psychology*, 133, 46-62.
- Roesch, M. R., Esber, G. R., Li, J., Daw, N. D., & Schoenbaum, G. (2012). Surprise! Neural correlates of Pearce-Hall and Rescorla-Wagner coexist within the brain. *European Journal of Neuroscience*, 35, 1190-1200.
- Ross-Sheehy, S., Oakes, L. M., & Luck, S. J. (2003). The development of visual short-term memory capacity in infants. *Child Development*, 874, 1807-1822.
- Rovee-Collier, C. (1999). The development of infant memory. *Current Directions in Psychological Science*, 8, 80-85.
- Ruff, H. A. & Capozzoli, M. C. (2003). Development of attention and distractibility in

- the first 4 years of life. *Developmental Psychology*, 39, 877-890.
- Saffran, J. R., Aslin, R. N., Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, 274, 1926-1928.
- Santos, L. R. (2004). 'Core knowledges': A dissociation between spatiotemporal knowledge and contact-mechanics in a non-human primate? *Developmental Science*, 7, 167-174.
- Santos, L. R., & Hauser, M. D. (2002). A non-human primate's understanding of solidity: Dissociations between seeing and acting. *Developmental Science*, 5, F1-F7.
- Santos, L.R., & Hood, B.M. (2009). Object representation as a central issue in cognitive science. In B.M. Hood & L.R. Santos (Eds.) *The origins of object knowledge: The Yale Symposium on the Origins of Object and Number Representation*. Oxford: Oxford University Press.
- Scholl, B. J., & Pylyshyn, Z. W. (1999). Tracking multiple items through occlusion: Clues to visual objecthood. *Cognitive Psychology*, 38, 259 - 290.
- Schultz, W., Dayan, P., & Montague, R. R. (1997). A neural substrate of prediction and reward. *Science*, 275, 1593-1599.
- Schultz, W. & Dickinson, A. (2000). Neuronal coding of prediction errors. *Annual Review of Neuroscience*, 23, 473-500.
- Schulz, L. E. (2012). The origins of inquiry: Inductive inference and exploration in early childhood. *Trends in Cognitive Sciences*, 16, 382-389.
- Schulz, L. E. & Bonawitz, E. B. (2007). Serious fun: Preschoolers engage in more exploratory play when evidence is confounded. *Developmental Psychology*, 43, 1045-1050.

- Senghas, A., Kita, S., & Özyürek, A. (2004). Children creating core properties of language: Evidence from an emerging sign language in Nicaragua. *Science*, 305, 1779-1782.
- Simpson, T., Carruthers, P., Laurence, S., & Stich, S. (2005). Introduction: Nativism past and present. In P. Carruthers, S. Laurence, & S. Stich (Eds.), *The innate mind: Structure and contents* (pp. 3-19). New York: Oxford University Press.
- Sirois, S. & Mareschal, D. (2002). Models of habituation in infancy. *Trends in Cognitive Sciences*, 6, 293-298.
- Skinner, B.F. (1977). Why I am not a cognitive psychologist. *Behaviorism*, 5, 1-10.
- Spelke, E. S. (1990). Principles of object perception. *Cognitive Science*, 14, 29-56.
- Spelke, E. S. (1994). Initial knowledge: Six suggestions. *Cognition*, 50, 431-445.
- Spelke, E. S. (1998). Nativism, empiricism, and the origins of knowledge. *Infant Behavior and Development*, 21, 181-200.
- Spelke, E. S., Breinlinger, K., Jacobson, K., & Phillips, A. (1993). Gestalt relations and object perception: A developmental study. *Perception*, 22, 1483-1501.
- Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, 99, 605-632.
- Spelke, E. S., Kestenbaum, R., Simons, D., & Wein, D. (1995). Spatiotemporal continuity, smoothness of motion and object identity in infancy. *British Journal of Developmental Psychology*, 13, 113-142.
- Spelke, E. S., & Kinzler, K. D. (2007). Core knowledge. *Developmental Science*, 10, 89-96.
- Spelke, E. S. & Lee, S. A. (2012). Core systems of geometry in animal minds.

Philosophical Transactions of the Royal Society, B., 367, 2784-2793.

- Spelke, E. S. & Newport, E. L. (1998). Nativism, empiricism, and the development of knowledge. In W. Damon. & R. M. Lerner (Eds.), *Handbook of child psychology: Volume 1: Theoretical models of human development (5th edition)* (pp. 275-340). Hoboken, NJ: John Wiley & Sons, Inc.
- Spelke, E. S, Phillips, A., & Woodward, L. (1995). Infants' knowledge of object motion and human action. In D. Sperber, D. Premack, & A Premack (Eds.), *Causal cognition: A multidisciplinary debate* (pp. 44-78). Oxford, UK: Clarendon Press.
- Spelke, E. S. & Van de Walle, G. (1993). Perceiving and reasoning about objects: Insights from infants. In N. Eilan, R. McCarthy, & W. Brewer (Eds.), *Spatial representation* (pp. 132-161). Oxford, UK: Basil Blackwell.
- Stahl, A. E. & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, 348, 91-94.
- Téglás, E., Vul, E., Girotto, V., Gonzalez, M., Tenenbaum, J. B., & Bonatti, L. L. (2011). Pure reasoning in 12-month-old infants as probabilistic inference. *Science*, 332, 1054–1058.
- Téglás, E., Girotto, V., Gonzalez, M., & Bonatti, L. L. (2007). Intuitions of probabilities shape expectations about the future at 12 months and beyond. *Proceedings of the National Academy of Sciences*, 104, 19156019159.
- Teller, D. Y. (1979). The forced-choice preferential looking procedure: A psychophysical technique for use with human infants. *Infant Behavior and Development*, 2, 135-153.
- Tenenbaum, J. B., Griffiths, T. L., & Kemp, C. (2006). Theory-based Bayesian models of

- inductive learning and reasoning. *Trends in Cognitive Sciences*, 7, 309-318.
- Tenenbaum, J. B., Kemp, C., Griffiths, T.L., & Goodman, N.D. (2011). How to grow a mind: Statistics, structure and abstraction. *Science*, 331, 1279-1285.
- Thomson, D. R., Smilek, D., & Besner, D. (2014). On the asymmetric effects of mind-wandering on levels of processing at encoding and retrieval. *Psychonomic Bulletin and Review*, 21, 728-733.
- Teinonen, T., Fellman, V., Näätänen, R., Alku, P., & Huotilainen, M. (2009). Statistical language learning in neonates revealed by event-related brain potentials. *BMC Neuroscience*, 10.
- Turk-Browne, N. B., Jungé, J. A., & Scholl, B. J. (2005). The automaticity of visual statistical learning. *Journal of Experimental Psychology: General*, 134, 552-564.
- van Marle, K. & Scholl, B. J. (2003). Attentive tracking of objects vs. substances. *Psychological Science*, 15, 498-504.
- van Schijndel, T. J., Visser, I., van Bers, B. M., & Raijmakers, M. E. (2015). Preschoolers perform more informative experiments after observing theory-violating evidence. *Journal of Experimental Child Psychology*, 131, 104-119.
- Wacongne, C., Labyt, E., van Wassenhove, V., Bekinschtein, T., Naccache, L., & Dehaene, S. (2011). Evidence for a hierarchy of predictions and prediction errors in human cortex. *Proceedings of the National Academy of Sciences*, 108, 20754-20759.
- Waeletti, P., Dickinson, A., & Schultz, W. (2001). Dopamine responses comply with basic assumptions of formal learning theory. *Nature*, 412, 43-48.
- Walden, T. Kim, G., McCoy, C., & Karass, J. (2007). Do you believe in magic? Infants'

- social looking during violations of expectations. *Developmental Science*, 10, 654-663.
- Wang, S., Baillargeon, R., & Brueckner, L. (2004). Young infants' reasoning about hidden objects: Evidence from violation-of-expectation tasks with test trials only. *Cognition*, 93, 167-198.
- Waxman, S. R., Lidz, J. L., Braun, I. E., & Lavin, T. (2009). Twenty-four-month-old infants' interpretations of novel verbs and nouns in dynamic scenes. *Cognitive Psychology*, 59, 67-95.
- Weiss, S. L., Robinson, G., & Hastie, R. (1977). The relationship of depth of processing to free recall in second and fourth graders. *Developmental Psychology*, 13, 525-526.
- Welder, A. N., & Graham, S. A. (2001). The influence of shape similarity and shared labels on infants' inductive inferences about nonobvious object properties. *Child Development*, 72, 1653-1673.
- Werker, J. F., Cohen, L. B., Lloyd, V., Casasola, M., & Stager, C. L. (1998). Acquisition of word-object associations by 14-month-old infants. *Developmental Psychology*, 34, 1289-130.
- Wilcox, T. (1999). Object individuation: Infants' use of shape, size, pattern, and color. *Cognition*, 72, 125-166.
- Wilcox, T., Bortfeld, H., Woods, R., Wruck, E., & Boas, D. A. (2005). Using near-infrared spectroscopy to assess neural activation during object processing in infants. *Journal of Biomedical Optic*, 10, 011010-1-011010-9.
- Wilcox, T., Nadal, L., & Rosser, R. (1996). Location memory in healthy preterm and

- full-term infants. *Infant Behavior & Development*, 19, 309-323.
- Wilson, P.N., Boumphrey, P., & Pearce, J.M. (1992). Restoration of the orienting response to a light by a change in its predictive accuracy. *Quarterly Journal of Experimental Psychology*, 44B, 17–36.
- Woodward, A. L. (1998). Infants selectively encode the goal object of an actor's reach. *Cognition*, 69, 1-34.
- Woodward, A. L., Phillips, A., & Spelke, E. S. (1993). Infants' expectations about the motions of inanimate vs. animate objects. *Proceedings of the Cognitive Science Society*. Hillsdale, NJ: Erlbaum.
- Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, 358, 749-750.
- Xu, F., & Denison, S. (2009). Statistical inference and sensitivity to sampling in 11-month-old infants. *Cognition*, 112, 97–104.
- Xu, F. & Garcia, V. (2008) Intuitive statistics by 8-month-old infants. *Proceedings of the National Academy of Sciences of the United States of America*, 105, 5012-5015.
- Xu, F. & Tenenbaum, J. B. (2007). Word learning as Bayesian inference. *Psychological Review*, 114, 245-272.

7. Curriculum Vitae

Aimee E. Stahl

Johns Hopkins University
Department of Psychological & Brain Sciences
3400 North Charles Street, 119 Ames Hall
Baltimore, MD 21218
Email: astahl4@jhu.edu
Phone: (410) 516-6007

Academic Appointments

August 2015 Assistant Professor, Department of Psychology
The College of New Jersey

Education

2010 - 2015 Johns Hopkins University
Ph.D., Psychological & Brain Sciences
Advisor: Lisa Feigenson

2010 - 2012 Johns Hopkins University
M.A., Psychological & Brain Sciences
Advisor: Lisa Feigenson

2005 - 2008 University of Delaware
Honors B.A., Psychology & Women's Studies
Magna Cum Laude, Phi Beta Kappa

Awards and Honors

2014 Johns Hopkins University: Graduate Representative Organization Travel Grant

2014 Johns Hopkins University: Robert S. Waldrop Junior Investigator's Award for excellence in research

2012 Johns Hopkins University: Mary Ainsworth Award for outstanding female graduate student

2011 - 2014 National Science Foundation Graduate Research Fellowship

2011 Society for Research in Child Development Student Travel Award

2008 University of Delaware: Award for most outstanding senior Psychology major

2008 University of Delaware: Women's Studies Award of Special Merit

2007 University of Delaware: Global Scholar Award

Publications

- Stahl, A. E.** & Feigenson, L. (2015). Observing the unexpected enhances infants' learning and exploration. *Science*, 348, 91-94.
- Stahl, A. E.**, Romberg, A. R., Roseberry, S., Golinkoff, R. M., & Hirsh-Pasek, K. (2014). Infants segment continuous events using transitional probabilities. *Child Development*, 85, 1821-1826.
- Stahl, A. E.** & Feigenson, L. (2014). Social knowledge facilitates chunking in infancy. *Child Development*, 85, 1477-1490.
- Song, L., Nazzi, T., Moukawane, S., Golinkoff, R. M., **Stahl, A. E.**, Ma, W., Hirsh-Pasek, K., & Connell, M. (2010). Sleepy vs. sleeping: Preschoolers' sensitivity to morphological cues for adjectives and verbs in English and French. *Proceedings of the Annual Boston University Conference on Language Development*. Somerville, MA: Cascadilla Press.
- In preparation*
- Stahl, A. E.** & Feigenson, L. Children learn more effectively following surprising than expected events.
- Stahl, A. E.** & Feigenson, L. Infants use cues of personal ownership to chunk objects in working memory.
- Konishi, H., **Stahl, A. E.**, Golinkoff, R. M., & Hirsh-Pasek, K. Individual differences on a non-linguistic event categorization task predict later motion verb comprehension.

Presentations

Oral Papers and Talks

- Stahl, A. E.** & Feigenson, L. (2014). Increases in infants' exploration and learning following surprising events. In Z. Sim (chair), Infants are active learners. *International Conference on Infant Studies*, Berlin, Germany.
- Stahl, A. E.**, Romberg, A. R., Ridge, K., Roseberry, R., Hirsh-Pasek, K., & Golinkoff, R. M. (2014). Where the action is: Infants segment dynamic events using transitional probabilities. In A. Pace (chair), Finding breaks in the action: Exploring multiple mechanisms for infant event segmentation. *International Conference on Infant Studies*, Berlin, Germany.
- Stahl, A. E.**, Roseberry, S., Golinkoff, R. M., & Hirsh-Pasek, K. (2011). Infants divide and conquer: Using transitional probabilities to segment events. In **A. E. Stahl** & S. Roseberry (chairs), Carving events for word learning: Discovering the mechanisms behind infant event segmentation. *Society for Research in Child Development*, Montreal, Canada.
- Song, L., **Stahl, A. E.**, Golinkoff, R. M., Ranganathan, S., & Hirsh-Pasek, K. (2011). Labeling facilitates 19- to 21-month-olds' categorization of intransitive human actions. In J. de Villiers (chair), The role of language in action and event concepts. *Society for Research in Child Development*, Montreal, Canada.
- Tynan, E., **Stahl, A. E.**, Rocek, L., Ma, W., Marshall, J., Marshall, S., Golinkoff, R. M., Hirsh-Pasek, K. (2009). The path to language: Infants categorize path in real-world events. *34th Annual Boston University Conference on Language Development*, Boston, MA.

Song, L., Nazzi, T., Moukawane, S., Golinkoff, R. M., **Stahl, A. E.**, & Ma, W. (2009). Sleepy vs. sleeping: Preschoolers' sensitivity to morphological cues for adjectives and verbs in English and French. *34th Annual Boston University Conference on Language Development*, Boston, MA.

Posters

- Stahl, A. E.** & Feigenson, L. (2015). Infants' selective exploration following surprising events. *Society for Research in Child Development*, Philadelphia, PA.
- Stahl, A. E.**, Kibbe, M. M., & Feigenson, L. (2015). Memory load and the precision of infants' working memory for object identities. *Society for Research in Child Development*, Philadelphia, PA.
- Stahl, A. E.** & Feigenson, L. (2013). Infants chunk objects using ownership cues. *Cognitive Development Society*, Memphis, TN.
- Stahl, A. E.** & Feigenson, L. (2013). Surprise! Infants learn more effectively following violation-of-expectation events. *Society for Research in Child Development*, Seattle, WA.
- Stahl, A. E.**, Taggart, J., & Feigenson, L. (2013). Surprising events boost preschoolers' word learning. *Society for Research in Child Development*, Seattle, WA.
- Johanson, M., Konishi, H., **Stahl, A. E.**, Golinkoff, R. M., & Hirsh-Pasek, K. (2013). Under, over, and in between: General vocabulary comprehension is linked to preposition comprehension. *Society for Research in Child Development*, Seattle, WA.
- Stahl, A. E.** & Feigenson, L. (2012). Can infants use social cues to chunk objects in working memory? *International Conference on Infant Studies*, Minneapolis, MI.
- Ranganathan, S., **Stahl, A. E.**, Shi, R., Golinkoff, R. M., & Hirsh-Pasek, K. (2012). Stem learning: Infants segment the morpheme /ing/ to identify a novel word. *International Conference on Infant Studies*, Minneapolis, MI.
- Konishi, H., **Stahl, A. E.**, Kosko, C., ITEL, N., Shaoul, K., Golinkoff, R. M., & Hirsh-Pasek, K. (2012). Individual differences on a nonlinguistic categorization task predict later language. *International Conference on Infant Studies*, Minneapolis, MI.
- Stahl, A. E.**, Ranganathan, S., Tynan, E., Kranjec, A., Cardillo, E., Chatterjee, A., Golinkoff, R. M., Hirsh-Pasek, K. (2011). Across the divide: Infants notice changes in manner and path in an occlusion event. *Society for Research in Child Development*, Montreal, Canada.
- Song, L., **Stahl, A. E.**, Connell, M., Golinkoff, R. M., & Hirsh-Pasek, K. (2011). Young children's sensitivity to morphological cues for adjectives and verbs in English: A developmental story. *Society for Research in Child Development*, Montreal, Canada.
- Ranganathan, S., **Stahl, A. E.**, Golinkoff, R. M., & Hirsh-Pasek, K. (2011). Which way? Examining infants' ability to discriminate path information in naturalistic events. *Society for Research in Child Development*, Montreal, Canada.
- Stuehling, A., Song, L., Moynihan, N., **Stahl, A. E.**, Golinkoff, R. M., & Hirsh-Pasek, K. (2011). What can children learn in children's museums? Different views from parents and experts. *Society for Research in Child Development*, Montreal, Canada.
- Stahl, A. E.**, Roseberry, S., Tynan, E., Song, L., Golinkoff, R. M., & Hirsh-Pasek, K. (2010). Breaking up is not hard to do: Transitional probabilities facilitate infants' dynamic event segmentation. *International Conference on Infant Studies*, Baltimore, MD.
- Stahl, A. E.**, Song, L., Tynan, E., Rocek, L., Ma, W., Wong, W., Golinkoff, R. M., & Hirsh-Pasek, K. (2010). Getting around: Infants categorize paths in realistic events. *International Conference on Infant Studies*, Baltimore, MD.
- Stahl, A. E.**, Tynan, E., Song, L., Wong, W., Golinkoff, R. M., & Hirsh-Pasek, K. (2010). Manner, interrupted: Infants detect manner changes in occlusion events. *International Conference on Infant Studies*, Baltimore, MD.
- Song, L., Golinkoff, R. M., **Stahl, A. E.**, & Hirsh-Pasek, K. (2010). All action and no talk: 10- to 12-month-olds can form nonlinguistic categories of hopping and marching. *International Conference on Infant Studies*, Baltimore, MD.
- Göksun, T., Tynan, E., Roseberry, S., George, N., Ferrara, K., **Stahl, A. E.**, Hirsh-Pasek, K., & Golinkoff, R. M. (2010). A new angle to infant causality. *International Conference on Infant Studies*, Baltimore, MD.
- Wong, W., McManaman, M., **Stahl, A. E.**, Golinkoff, R. M., Newcombe, N., & Hirsh-Pasek,

- K. (2010). Triangles as pizza slices, circles in clocks: Representational complexity in children's recognition of shapes. *International Conference on Infant Studies*, Baltimore, MD.
- Wong, W., Dewson, G., Monahan, M., Shi, T., **Stahl, A. E.**, Golinkoff, R. M., Newcombe, N., & Hirsh-Pasek, K. (2010). The square goes here! Language and action scaffolding during shape play with traditional and electronic shape sorting toys. *International Conference on Infant Studies*, Baltimore, MD.
- Wong, W., Ma, W., **Stahl, A. E.**, Song, L., Strober, D., Rocek, L., Bosse, S., Golinkoff, R. M., Hirsh-Pasek, K. (2009, April). Extraction of path and manner from naturalistic events: Going where how? *Society for Research in Child Development*, Denver, CO.
- Ma, W., Golinkoff, R. M., Hirsh-Pasek, K., Wong, W., Song, L., **Stahl, A. E.**, Strober, D., Bither, K. (2009). Meaning specificity: How does it affect children's verb learning and extension? *Society for Research in Child Development*, Denver, CO.

Invited Talks

- 2015 National Living Laboratory Academic Meeting, Philadelphia, PA
- 2014 National Living Laboratory Introduction and Implementation Meeting, Baltimore, MD
- 2014 Rutgers University-Newark Developmental Psychology Brownbag series
- 2012 NSF Living Lab Initiative National Meeting, Boston, MA

Teaching

Johns Hopkins University

Sole instructor

- Summer 2014, Winter 2015 Origins of Social Cognition (independently designed and taught)
- Winter 2014 Infant Social Cognition (independently designed and taught)

Section instructor

- Spring 2011, 2012 Foundations of Mind

Teaching assistant

- Fall 2011, 2012 Introduction to Developmental Psychology
- Spring 2010 Origins of Human Sexuality

University of Delaware

Teaching assistant

- Spring 2008 Measurement & Statistics; Brain & Behavior

Mentorship

Mentee	Role	Undergrad. Institution	Current education or work
Carli Heiman	RA	Johns Hopkins University	B.A. Cognitive Science
Marisa Santoru	RA	Johns Hopkins University	B.A. Neuroscience
Susan Folsom	RA	Johns Hopkins University	M.A. School Psychology, Towson U.
Julissa Veras	RA	Johns Hopkins University	Lab Manager, Columbia
Alexa Lantiere	RA	Johns Hopkins University	B.A. Public Health
Krista Grubb	Intern	Johns Hopkins University	B.A. Cognitive Science
Bridget McGowan	RA	Johns Hopkins University	M.D., Case Western Reserve Univ.
Grace Lisandrelli	Intern	University of Rochester	Developmental Lab Manager, MIT
Claire Veazey	Intern	UNC	Clinical Lab Manager, UNC
Jessica Taggart	RA	Johns Hopkins University	Ph.D. Developmental Psych., UVA

Previous Academic Positions

2008 - 2010	Laboratory Coordinator, University of Delaware (Roberta M. Golinkoff)
2007 - 2008	Undergraduate Research Assistant, University of Delaware (Paul C. Quinn)
2007	Undergraduate Research Assistant, University of Delaware (Steven Most)
2006-2007	Undergraduate Research Assistant, University of Delaware (Adele Hayes)
2006	Undergraduate Research Assistant, University of Delaware (Lawrence Cohen)

University & Academic Service

2011 - 2014	Annual Brain Awareness Week presentation Baltimore Polytechnic High School, Baltimore, MD
2012 - 2013	Colloquium Committee Psychological & Brain Sciences, Johns Hopkins University
2011 - 2013	Student Organizer, Prospective Graduate Student Weekend Psychological & Brain Sciences, Johns Hopkins University
2006 - 2008	Peer Advisor Psychology Department, University of Delaware

Professional Affiliations

Society for Research in Child Development
Cognitive Development Society
International Society for Infant Studies